

- Stars and Supernovae -

NOAJ Astrophysics Lecture Series, November 2013

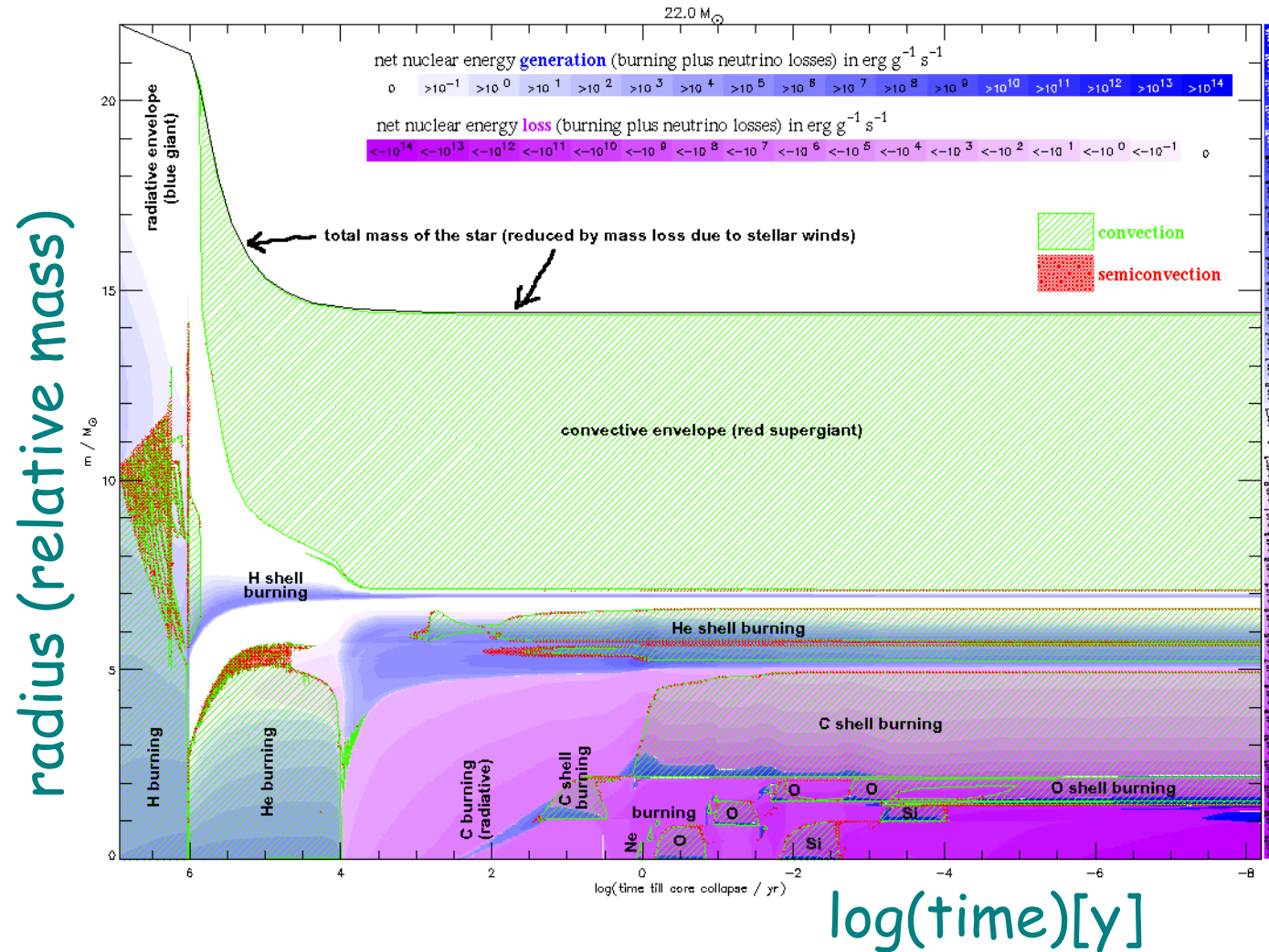
**Introduction to Observational Nuclear Astrophysics
Lecture #5**

by Roland Diehl

What Determines Stars...

★ Nuclear Energy Release

– Structure of Stars



Massive-Star Interior-Structure Issues



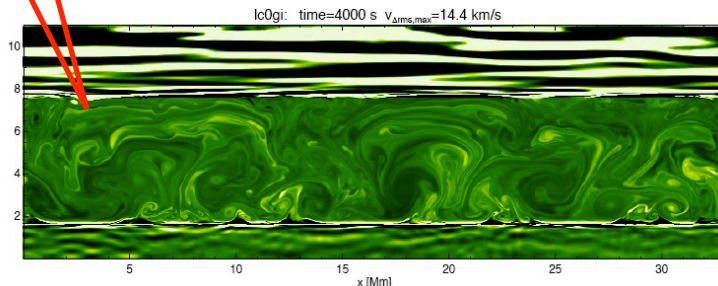
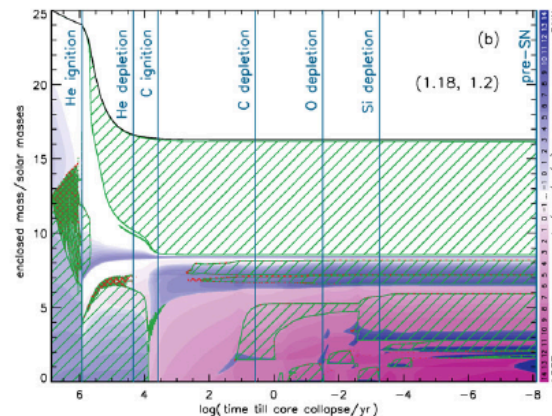
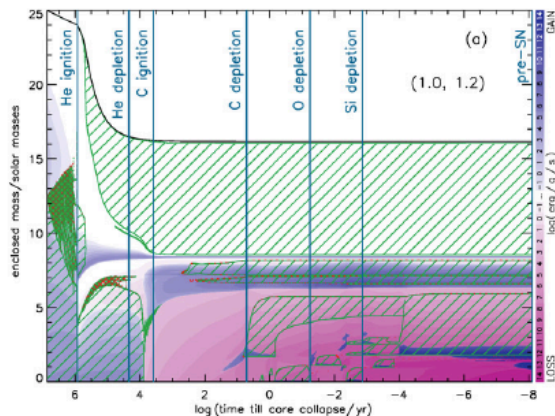
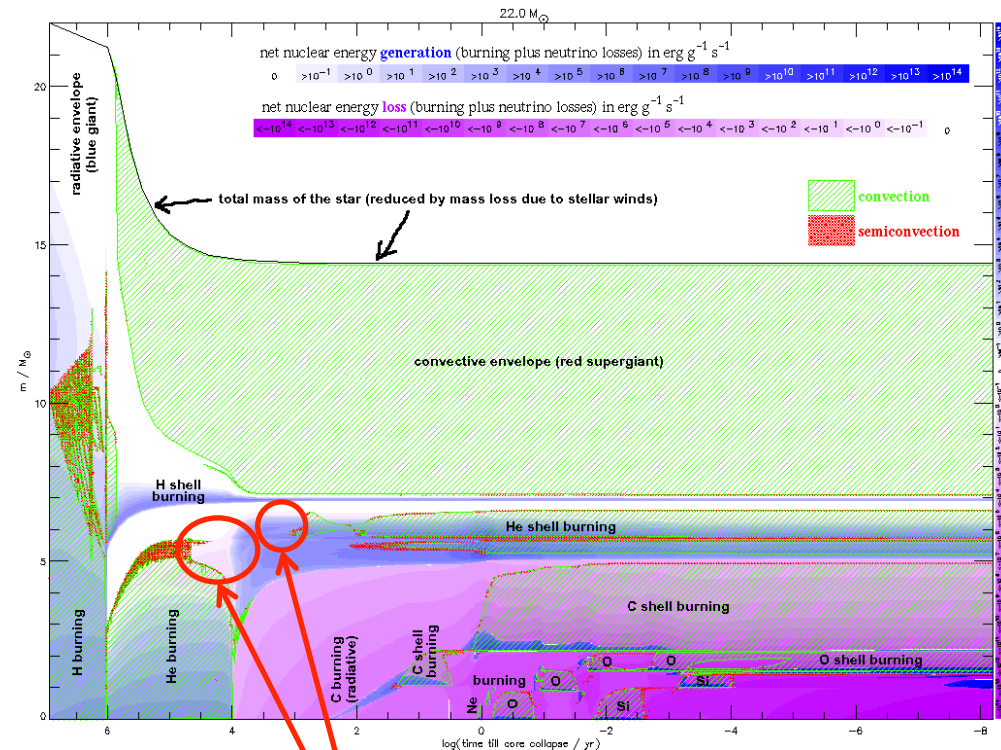
★ Convection transition into stable (radiative) layer?

👉 Empirical "Overshoot" and "Semiconvection" Parameters

★ Stellar rotation and mixing processes (3D)

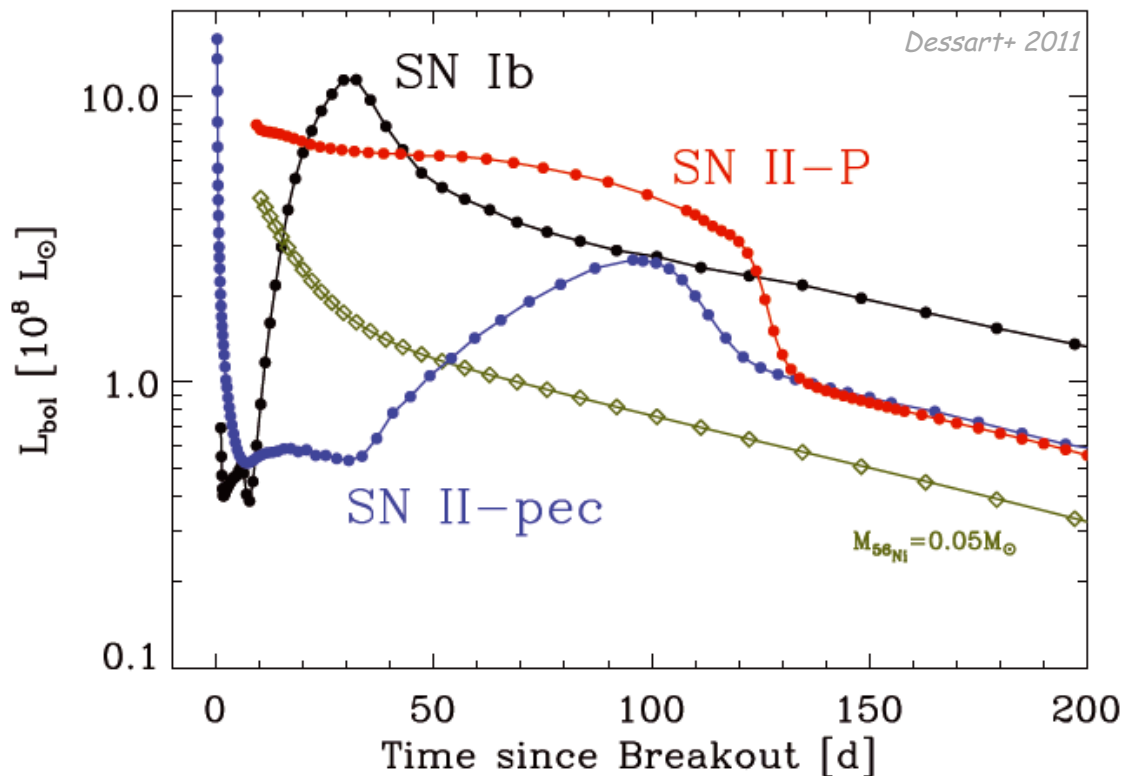
★ Impacts of 3α and $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ nuclear reaction rates

→ Shell burnings:
isolated or merged?



SN Light and ^{56}Ni

- Radioactive Decay of ^{56}Ni Powers SN Light
- The Conversion Depends on
 - ☞ Amount of ^{56}Ni Synthesized in the Explosive Burning
 - ☞ Spatial Distribution / Mixing of ^{56}Ni within Expanding Envelope
 - ☞ Structure & Morphology of the Envelope



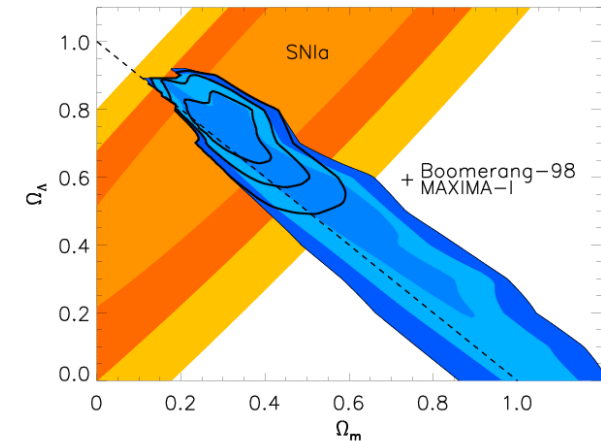
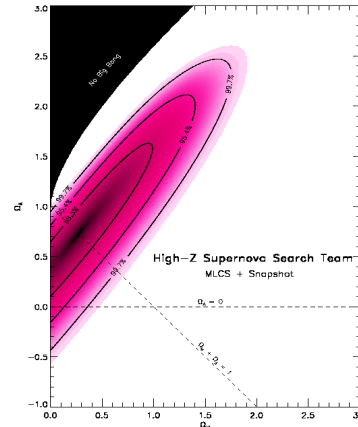
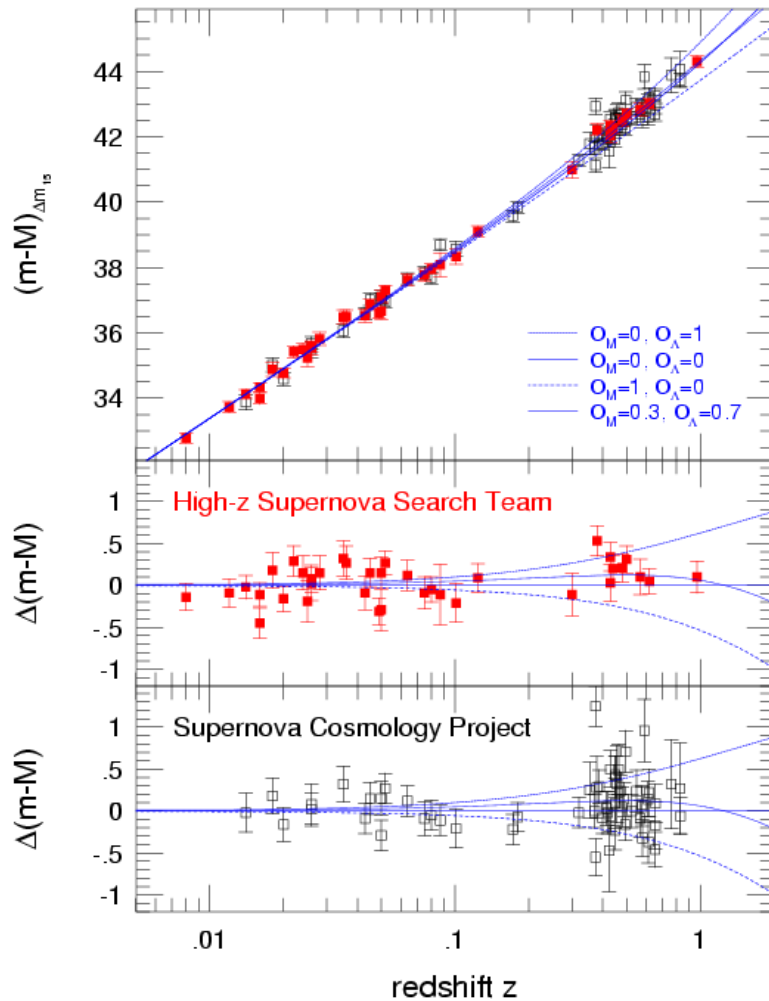
(from simulations of energy conversions)

Progenitor Envelopes are Different:

SN Ib: $\sim 10 R_{\odot}$
 SN II pec: $\sim 50 R_{\odot}$
 SN II P: $\sim 800 R_{\odot}$

★ Bolometric Light is not Directly/Simply Linked to ^{56}Ni Mass

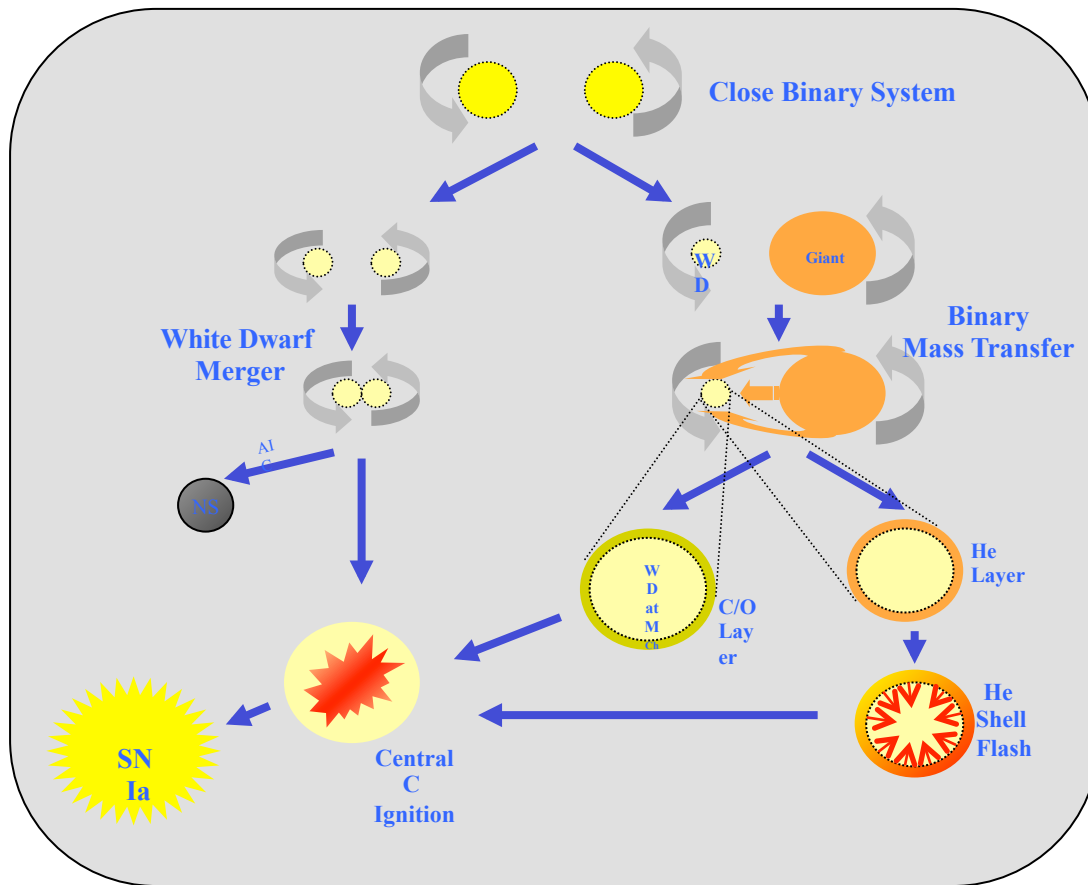
Supernovae Ia and Cosmology



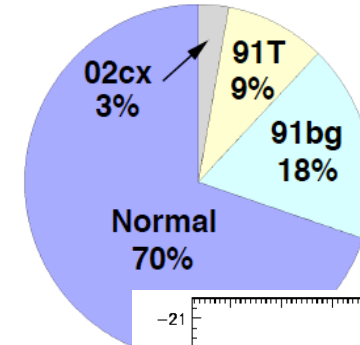
- Use Thermonuclear Explosions of CO-White-Dwarfs as Standard Candles
- Test Expansion History of Universe (flat, but $L > 0$?)
- Issues
 - ★ We Don't Understand the SN Explosion. Is the dm_{15} Calibration Good Enough?
 - ★ How is the C+O Nuclear-Fusion Energy Converted into Light & E_{kin} ?

SN Ia: Model Issues

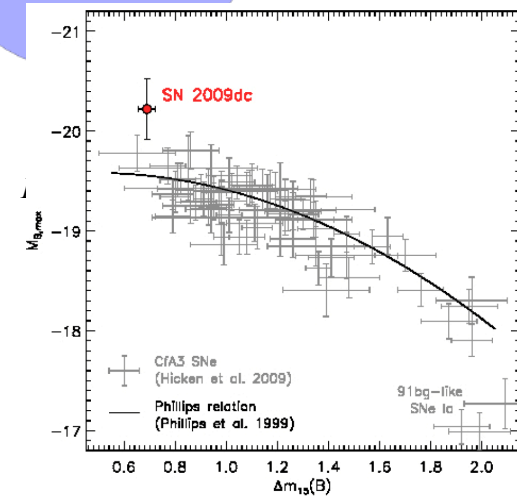
Progenitor Diversity?



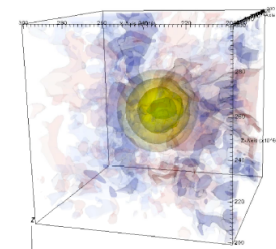
SN Ia Types



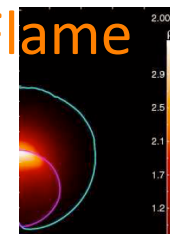
outliers?



Ignition?



Flame

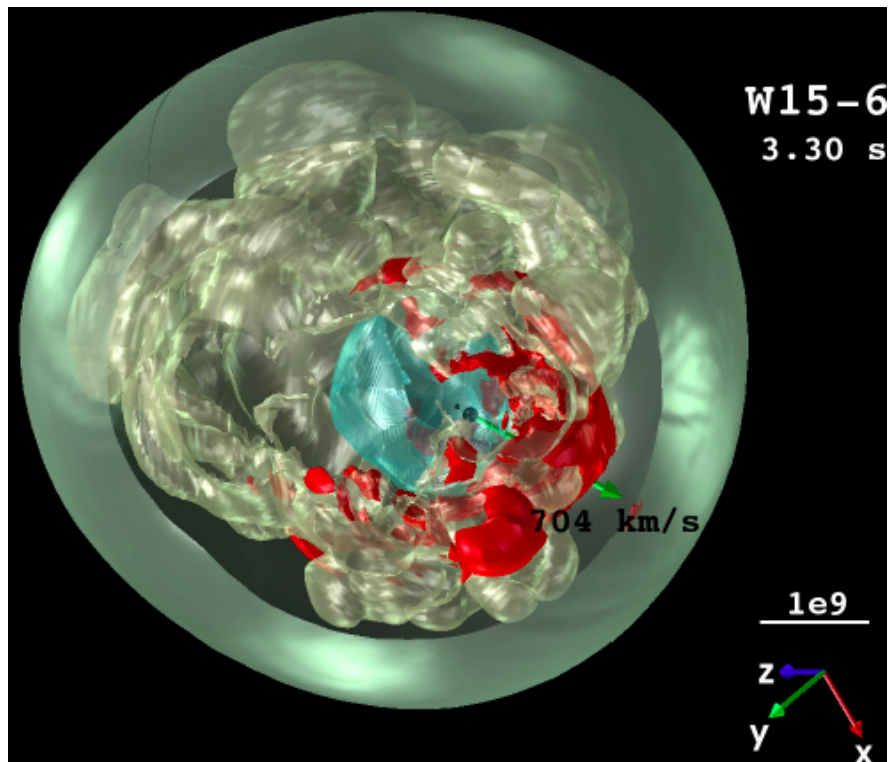


propagation?

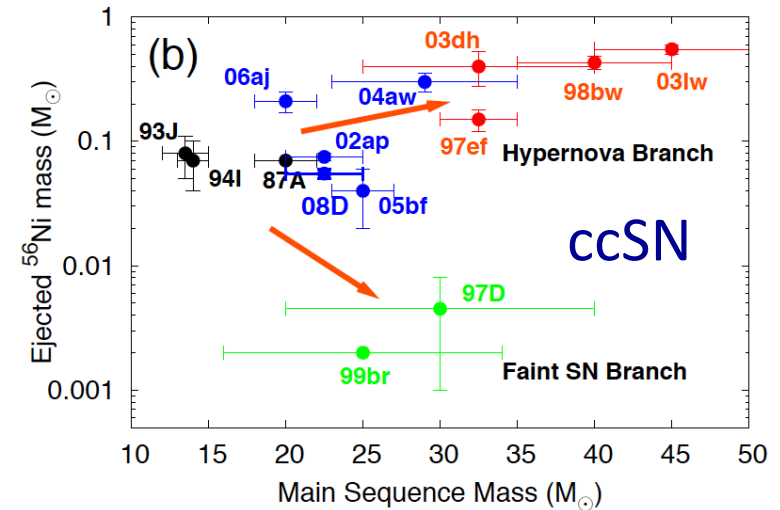
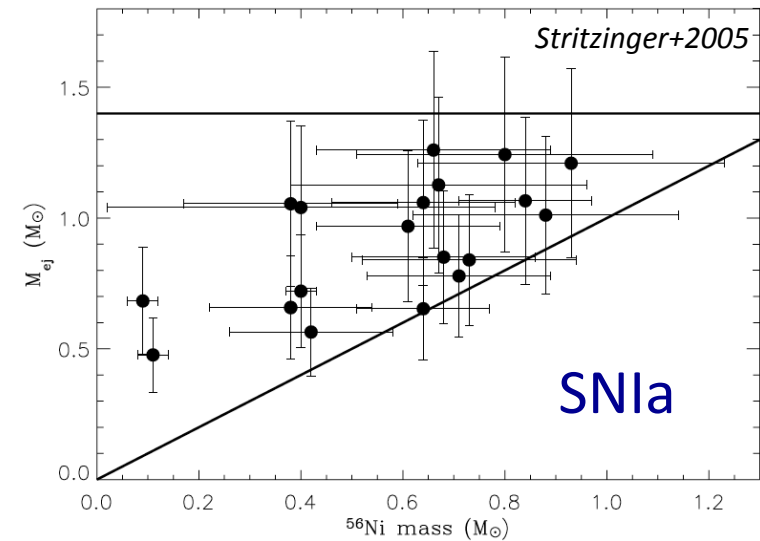
Supernova Explosion Issues



- Supernova Explosions
 - ★ $^{56}\text{Ni} \rightarrow \text{SN Light}$
 - ★ Explosion Dynamics, Structure



Wongwhatanarat+2013



Nomoto+2009

Supernova Explosion Issues



- Supernova Explosions

★ $^{56}\text{Ni} \rightarrow \text{SN Light}$

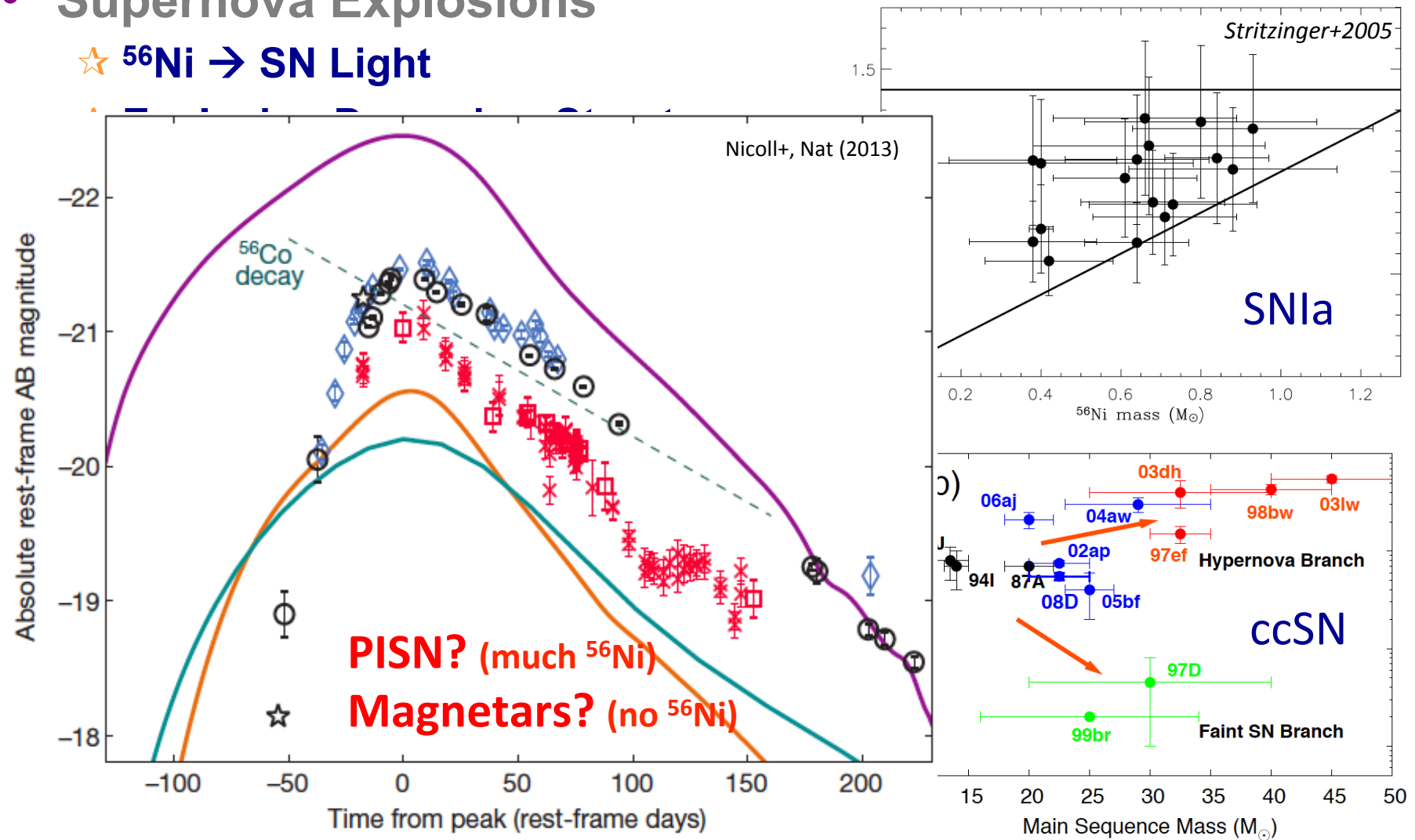


Figure 1 | Optical light curves of slow-fading super-luminous supernovae.

Stars and Supernovae

- **Stellar Structure and Evolution**
- **The $^{60}\text{Fe}/^{26}\text{Al}$ Ratio**
- **Core-Collapse Supernovae**
- **The ^{44}Ti Yield, SNR Morphology & Kinematics**
- **SN Ia**
- **^{56}Ni Gamma-Rays**

Stars: Hydrostatic Equilibrium

★ Gravity is balanced by pressure:

$$\frac{dP}{dm} = -\frac{GM}{4\pi \cdot r^4} \rightarrow 4\pi \cdot r^3 dP = -\frac{GM}{r} dm$$

$$dP = -\frac{GM\rho}{r^2} dr$$

internal gas energy versus gravitational energy

★ The spherical structure of a star:

☞ Mass-Radius Relation: $4\pi \cdot r^2 \rho = dM/dr$

★ An "Equation of State"

☞ Pressure and its relation to the other quantities:

☞ "polytropes"

$$P = K \cdot \rho^{1+\frac{1}{n}}$$

. = where heat capacity is constant $dQ = CdT$
then:

$$P \cdot V^{\gamma'} = \text{const} \quad \gamma' = \frac{C_p - C}{C_v - C}$$

- » Lane, Emden: if polytropic relation -> stellar structure is computable
- » Polytropic index n depends on material

☞ More General:

$$P = P(\rho, T)$$

- Effects of Energy Transport, Energy Generation, Composition
- i.e.: only simplified approximations lead to polytropes; reality is complex

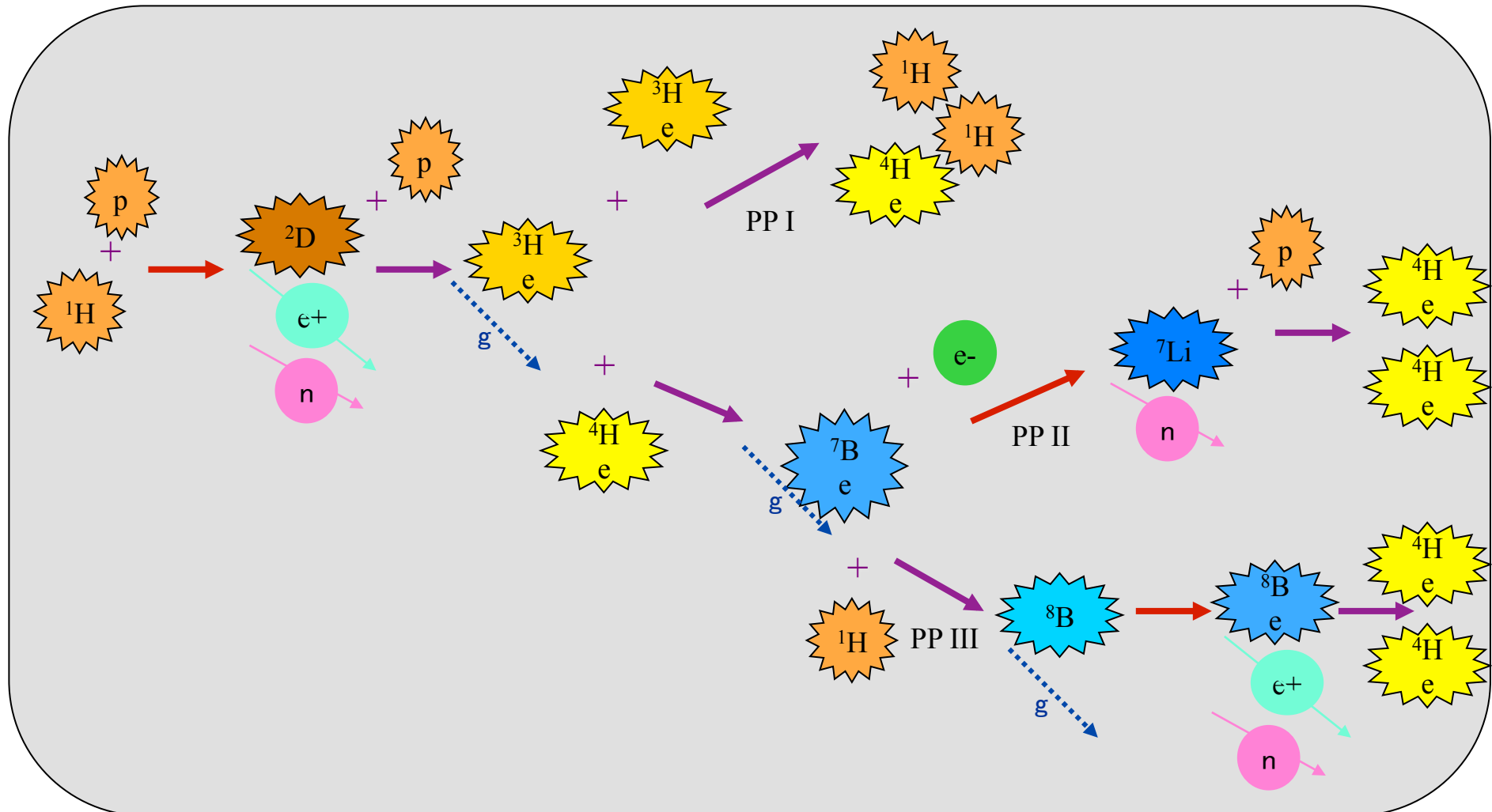
★ General for Normal Stars:

☞ Nuclear Energy Generation in Core (and Shells)

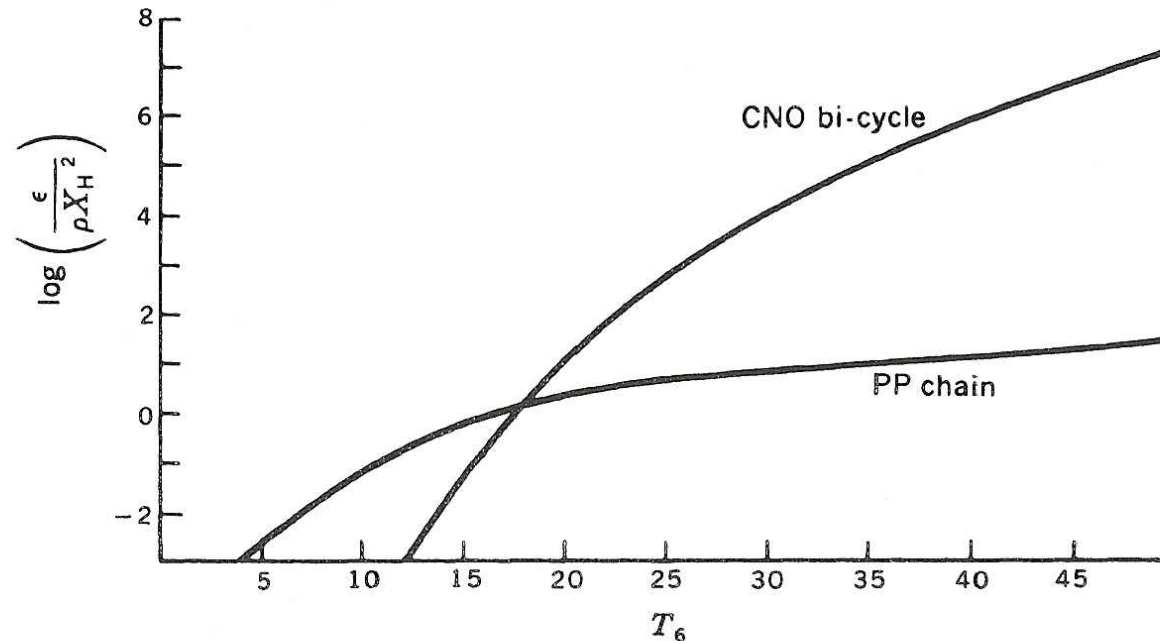
Nuclear Burning: H to He



- H Burning: p-p Chains



H-Burning: Halting Initial Gravitational Collapse



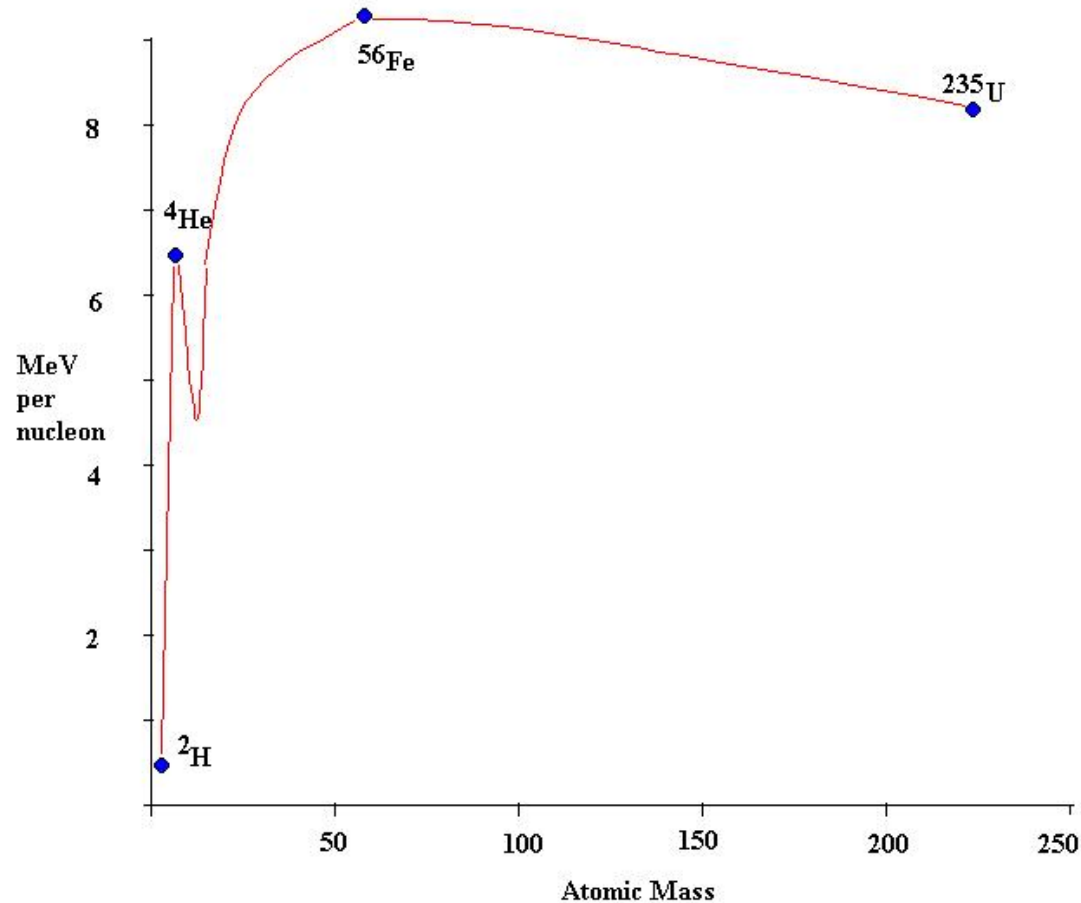
A comparison of thermonuclear power from the PP chains and the CNO cycle. Both chains are assumed to be operating in equilibrium. The calculation was made for the choice $X_{\text{CN}}/X_{\text{H}} = 0.02$, which is representative of population I composition.

★ For Metal-free Stars:

👉 **pp Chain Energy Insufficient**

👉 **Simultaneous H and He Burning to Counteract Gravity**

Nuclear Binding Energy



The binding energy is a measure of the force holding the nucleus of an atom together.

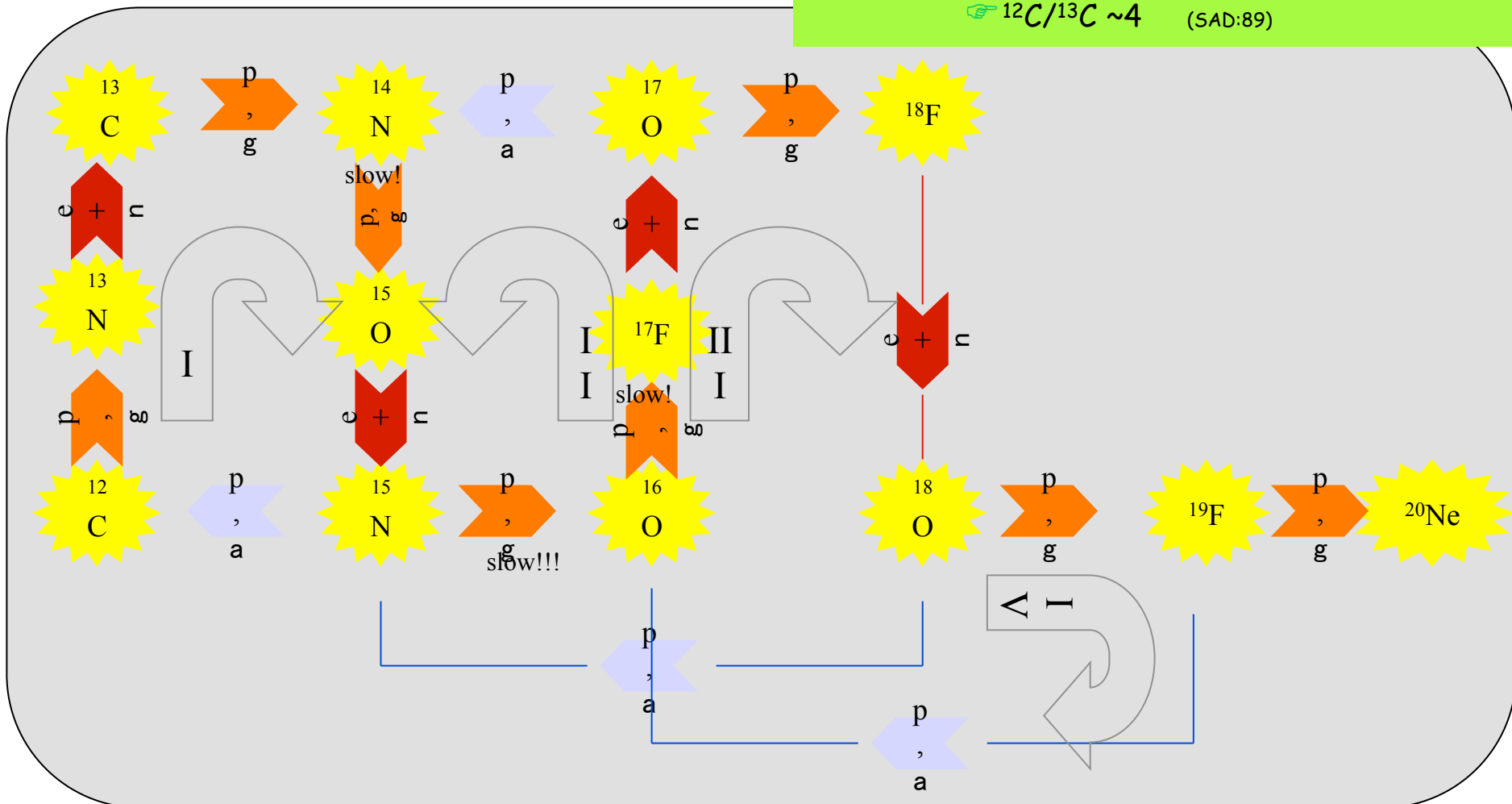
- The higher the binding energy, the more tightly bound is the nucleus.
- The most tightly bound nucleus of all is ^{56}Fe .
- Elements with atomic masses less than 56 can undergo fusion to form elements that are more stable.
- Elements with atomic masses greater than 56 can release energy when they undergo fission.

Nuclear Burning: H to He



- H Burning: CNO Cycle

➡ Consuming p (H), generating α (He)
 ➡ Net Burning towards ^{14}N
 ➡ $^{12}C/^{13}C \sim 4$ (SAD:89)



How much Energy due to H burning?

- $4 ({}^1\text{H}) \rightarrow {}^4\text{He} + 2 e^+ + 2 \text{ neutrinos} + \text{energy}$
- Energy released = 25 MeV per ${}^4\text{He}$ atom produced
 $= 4 \times 10^{-12}$ Joules
 $= 1 \times 10^{-15}$ Calories

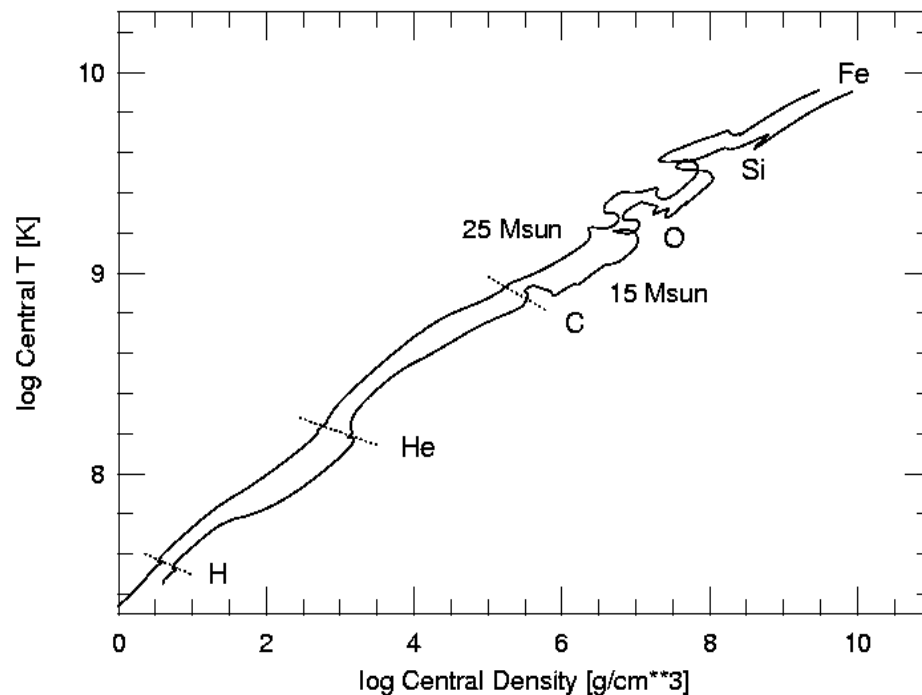
★ Within the Sun does this occurs 10^{38} times a second !

★ The Sun has 10^{56} H atoms to burn !

👉 Main Sequence Lifetime of the Sun ~ 8 Gy



What is a massive star?



Stars are gravitationally confined thermonuclear reactors

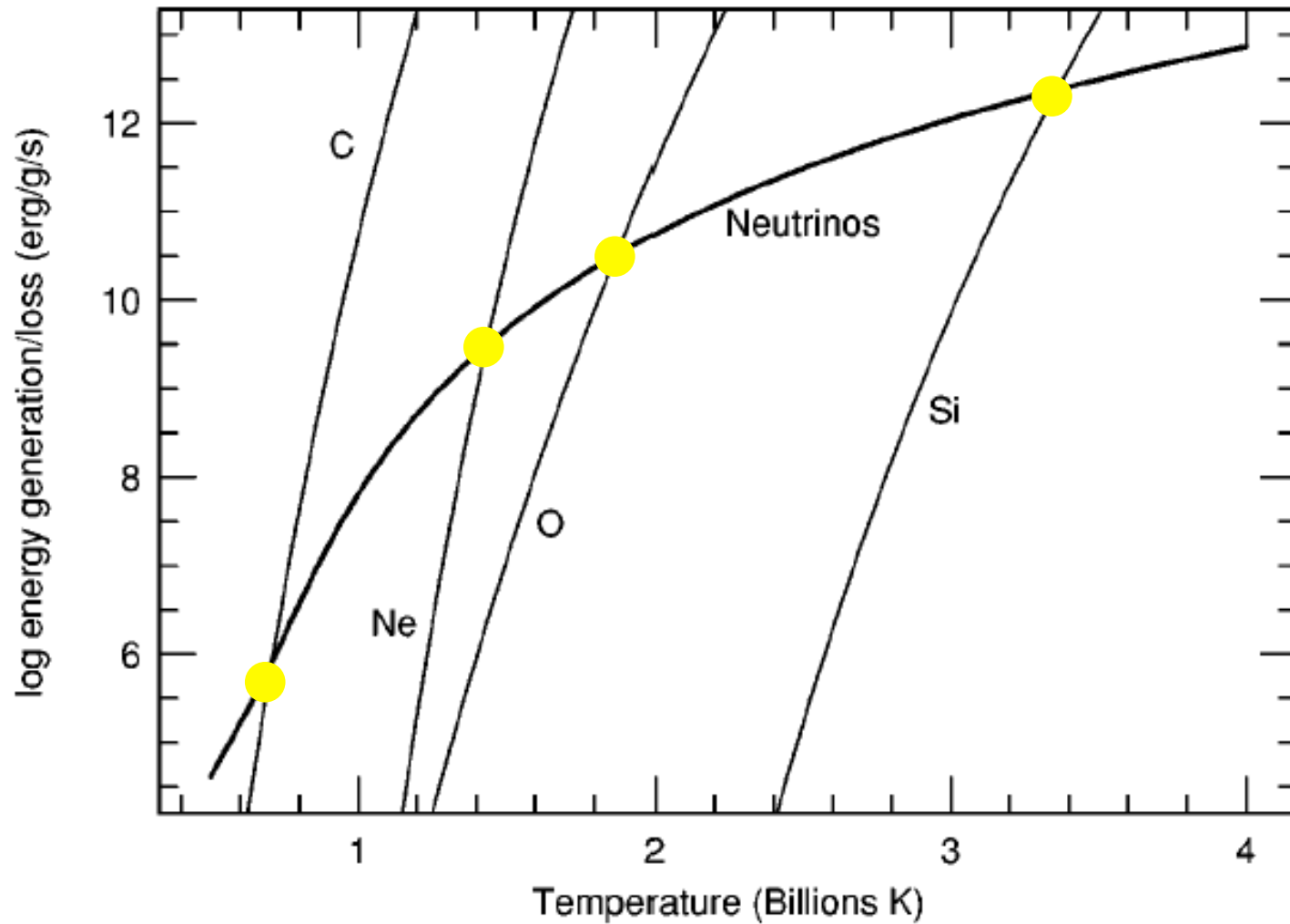
Each time one runs out of one kind of fuel, contraction and heating ensue, unless degeneracy is encountered.

For a star over $8 M_{\odot}$ contraction and heating continue until a Fe core is made

Gravitational collapse ensues, after no energy-providing fuel is left

courtesy SEWoosley

Hydrostatic Balance: Nuclear Energy versus Radiative Loss



● Burning stages
Slope defines temperature sensitivity of nuclear burning

Advanced Nuclear Burning Stages

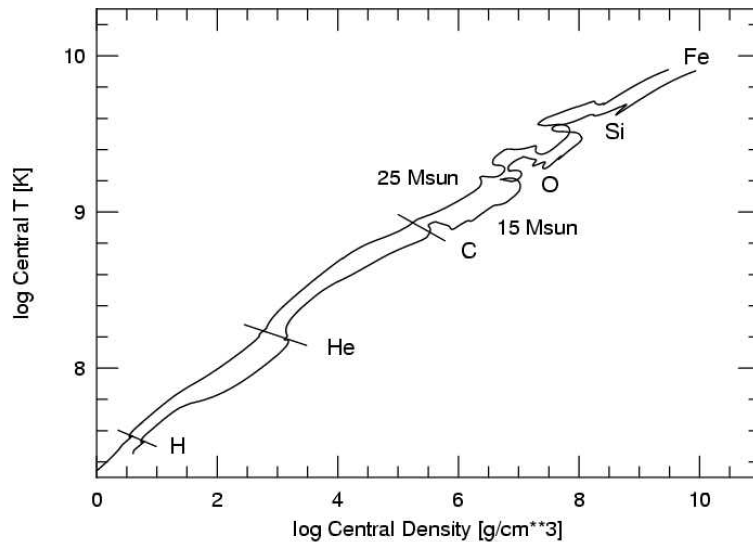
(e.g., 20 solar masses)

Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)
H	He	^{14}N	0.02	10^7
He	C, O	$^{18}\text{O}, ^{22}\text{Ne}$ s- process	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week

Reminder: Stellar Evolution

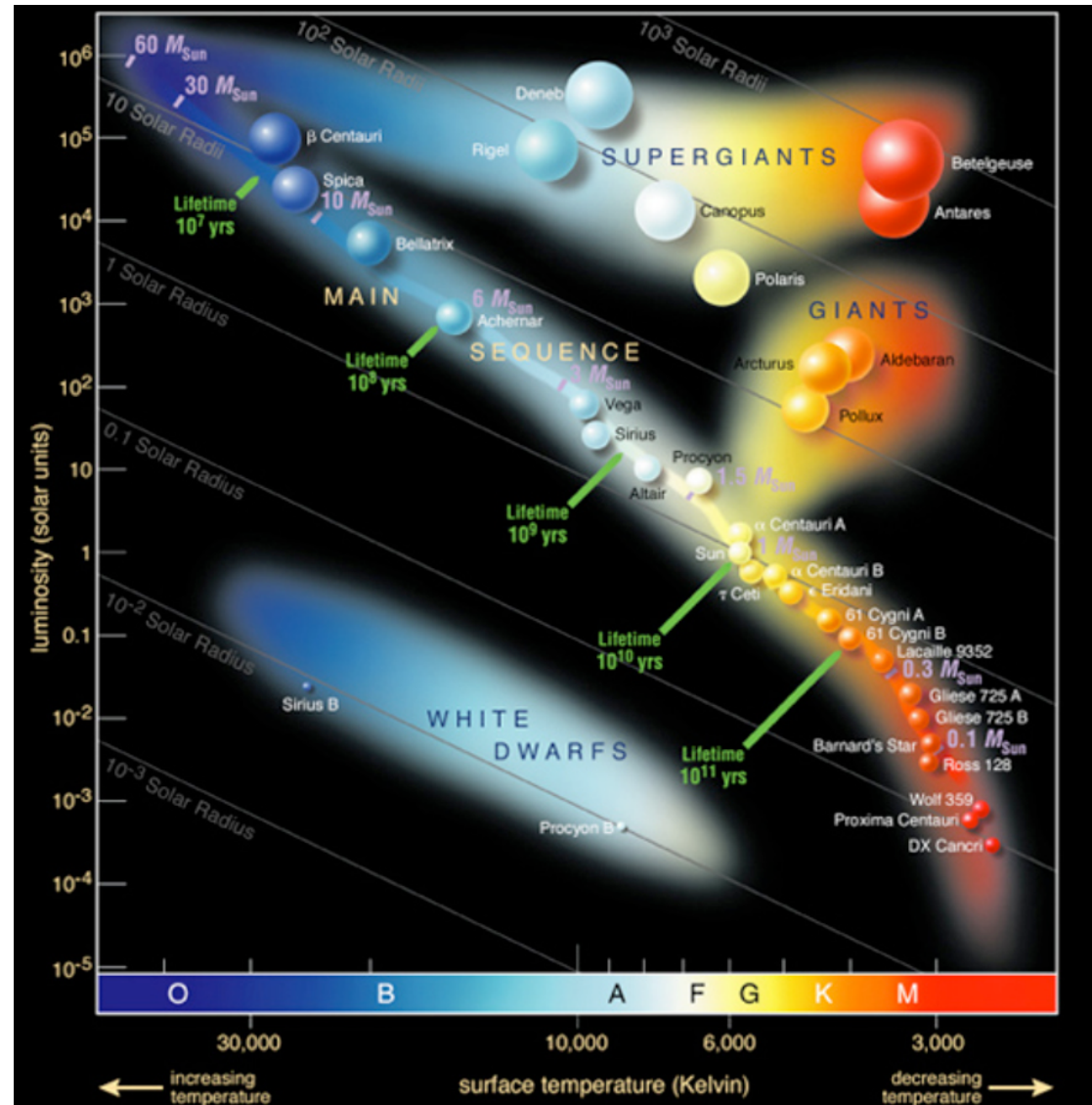


★ Stellar Evolution Describes the Track of Gravitationally-Confined Nuclear Reaction Sites



★ Configurations:

- ☞ Main-Sequence Stars
- ☞ Giant Stars
- ☞ Compact Stars



Branches of Stellar Evolution

★ Total Mass Determines...

- ☞ Ignition of Nuclear Fuel (Temperature, from Gravitational Compression)
- ☞ Degeneracy of Electrons in Core (Size of Core)

★ Physical Processes which Shape Stellar Evolution:

- ☞ Nuclear Burning
- ☞ Mass Loss

★ Low-Mass Stars [$M < 2.3 M_{\odot}$]

- ☞ Ignition of H
- ☞ He Core Becomes Degenerate Before Ignition

★ Intermediate-Mass Stars [$3 M_{\odot} < M < 8 M_{\odot}$]

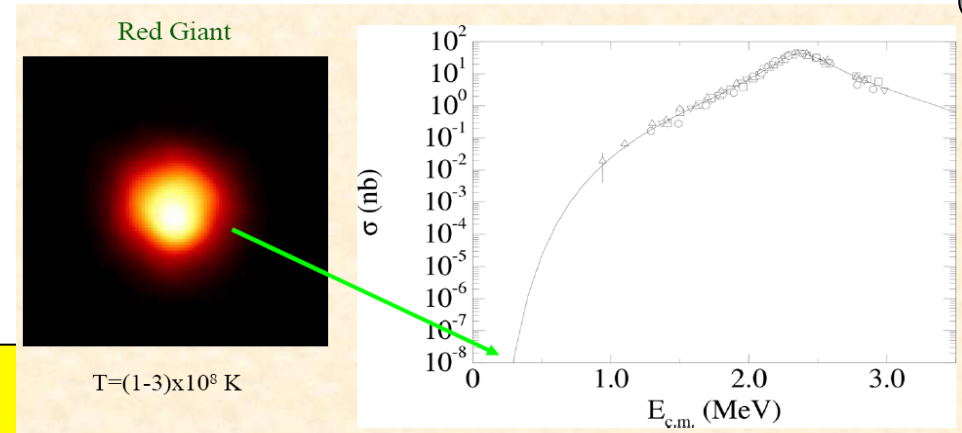
- ☞ Ignition of H, He, C, O
- ☞ White Dwarf Remnant

★ High-Mass (Massive) Stars [$M > 8 \dots 11 M_{\odot}$]

- ☞ Ignition of H,...Si
- ☞ Core Collapse Supernova, NS or BH Remnant

He Burning

- 3a Cycle



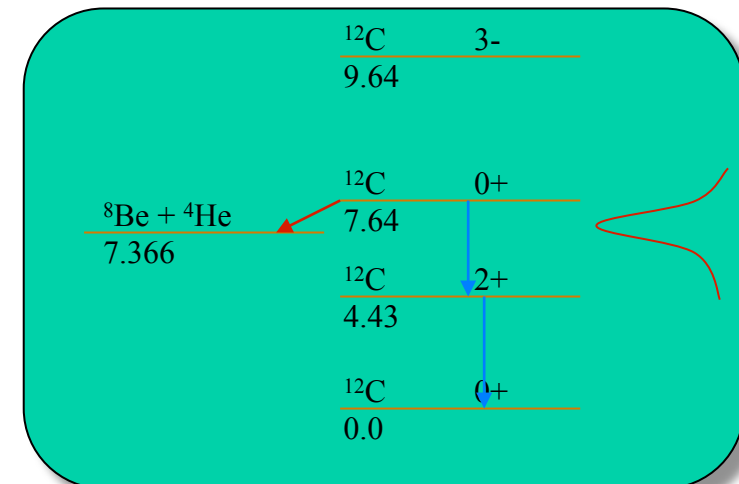
☞ Lifetime ${}^8\text{Be} \sim 7 \cdot 10^{-16} \text{ s}$ (-> “3-body-reaction” feasible!)

☞ ${}^8\text{Be}(\alpha, \text{gg}) {}^{12}\text{C}$ through Excited Level at 278 keV+ (Salpeter, Hoyle)

☞ $d\epsilon/dt \sim T_8^{40} \rightarrow$ **He Flash**

☞ Net Energy: $\sim 7.3 \text{ MeV}$
(BE ${}^4\text{He}$: 28.3 MeV, ${}^{12}\text{C}$: 92.2 MeV)

☞ Steady Burning:
Red Giant Stars

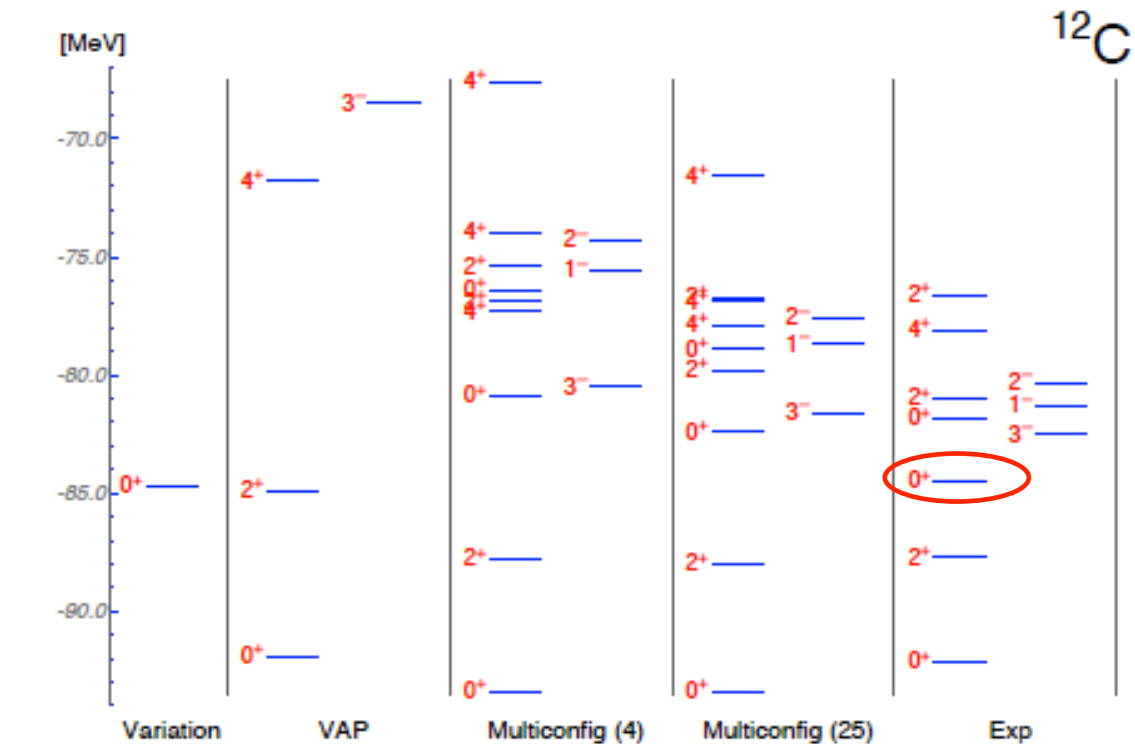
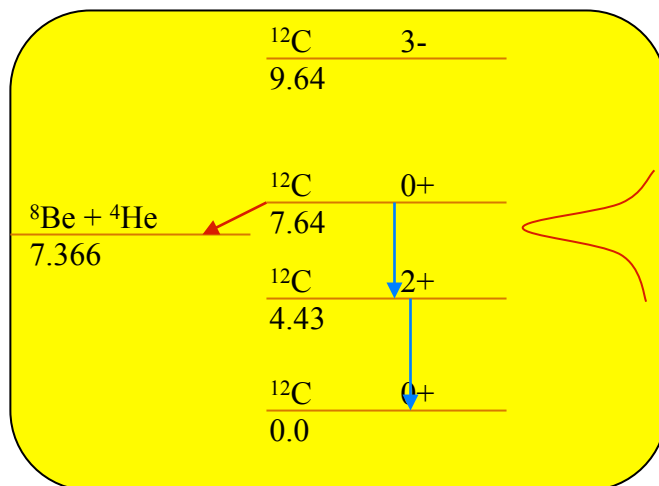


☞ Accreted Envelopes $\sim 10^{-4} M_{\odot} \rightarrow E_{\text{nuc}} \sim 10^{45} \text{ erg}$ from He flash

☞ (WD Masses 0.5...1.4 $M_{\odot} \rightarrow E_{\text{nuc}} \sim \text{few } 10^{49} \text{ erg}$ from He burning, $\sim 10^{53} \text{ erg}$ from C burning)

Ab-Initio Nuclear Models: ^{12}C

- ☆ Energy Levels still off by several MeV
- ☆ a Cluster Structure is Important
- ☆ The "Hoyle" State's Nature is Unknown



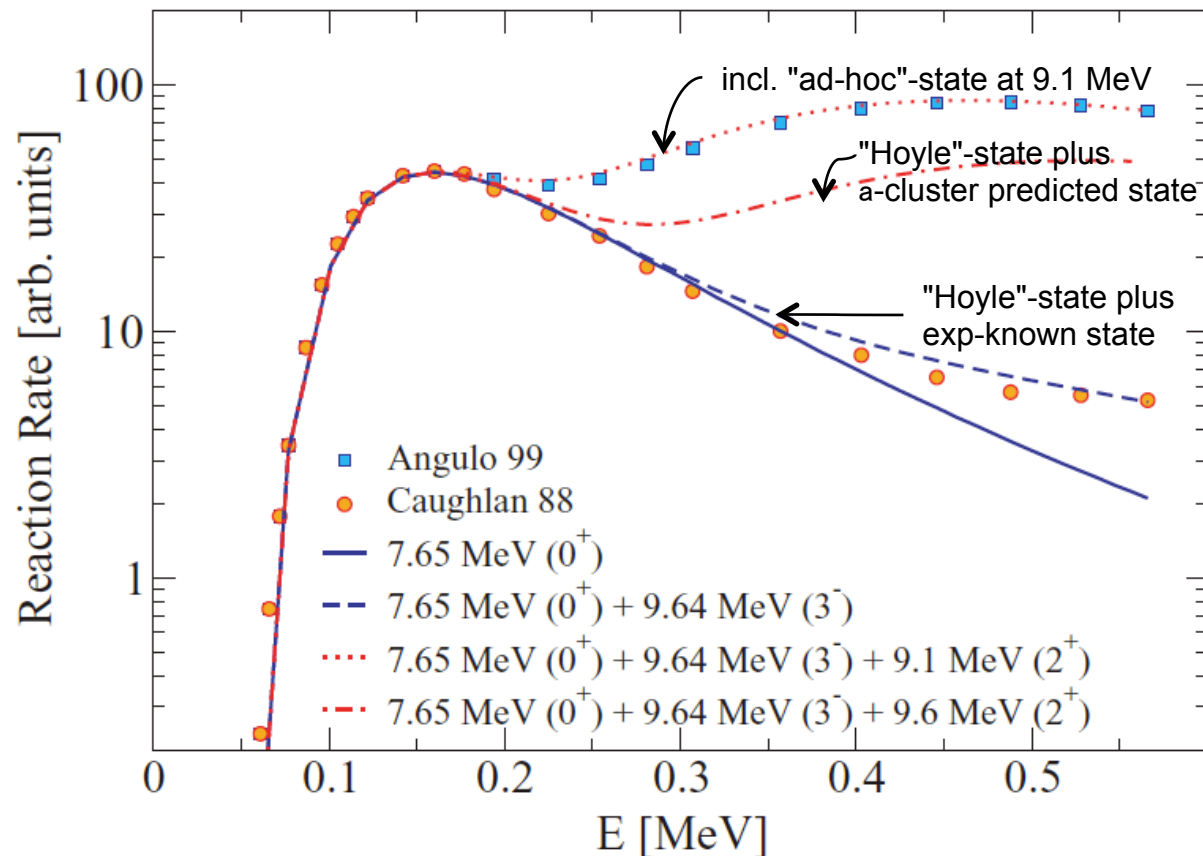
Feldmeier et al.

2008

Figure 6. Calculated and experimental level scheme for ^{12}C .

The Rate of $3\alpha \rightarrow {}^{12}\text{C}$

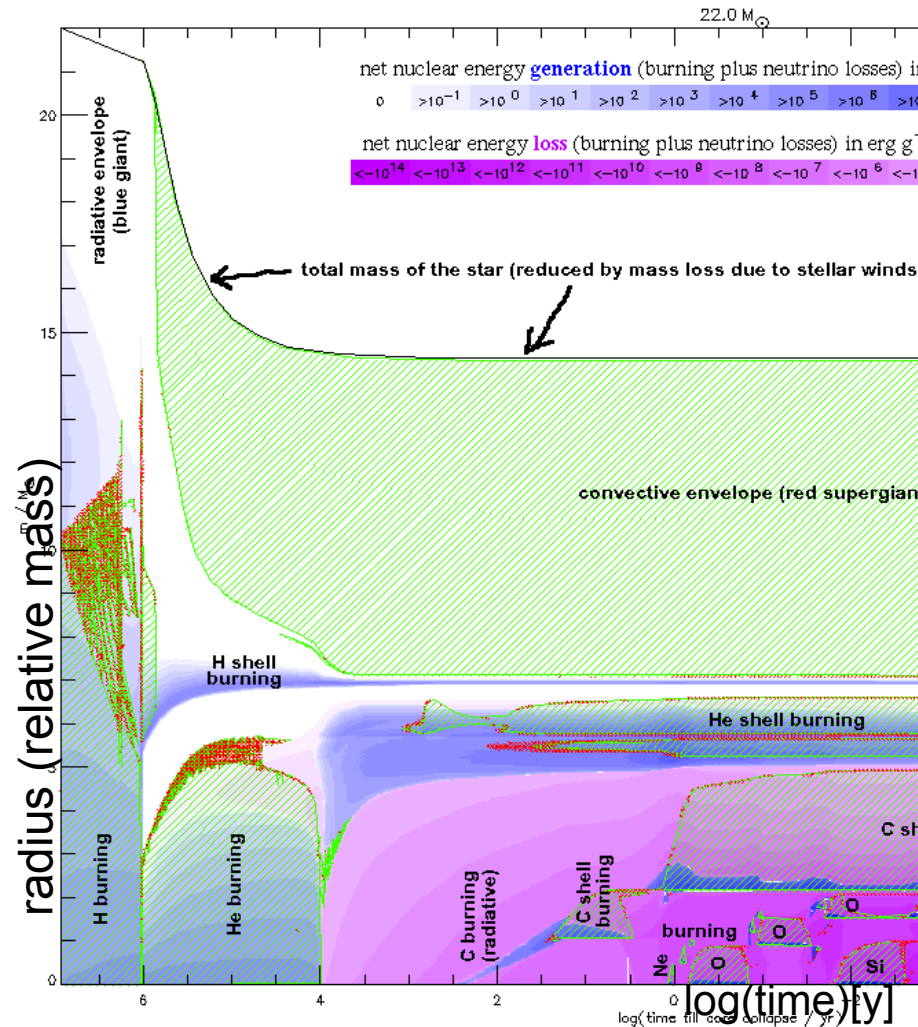
- ☆ "Hoyle" state at 7.65 MeV not Expected by Theories
- ☆ More States from a Cluster Admixtures?
- ☆ "Gamow" Window at ~ 300 keV \rightarrow Rate Uncertainty \sim Factor 7



Stellar Structure Complexities

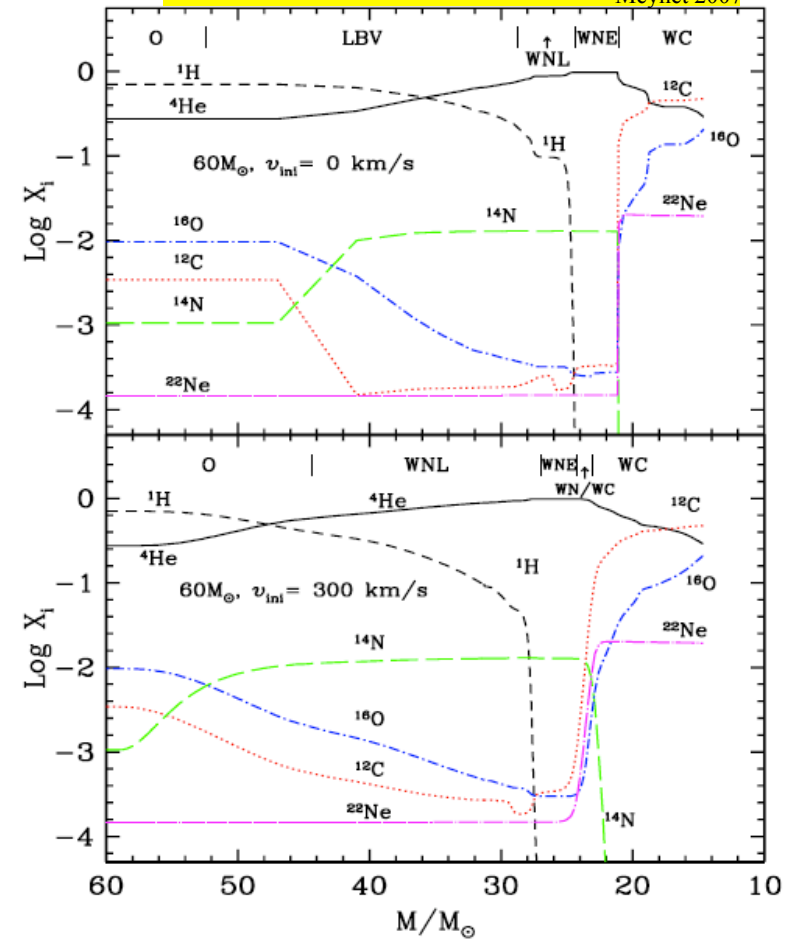


★ Stellar Rotation Incurs Structural Changes!



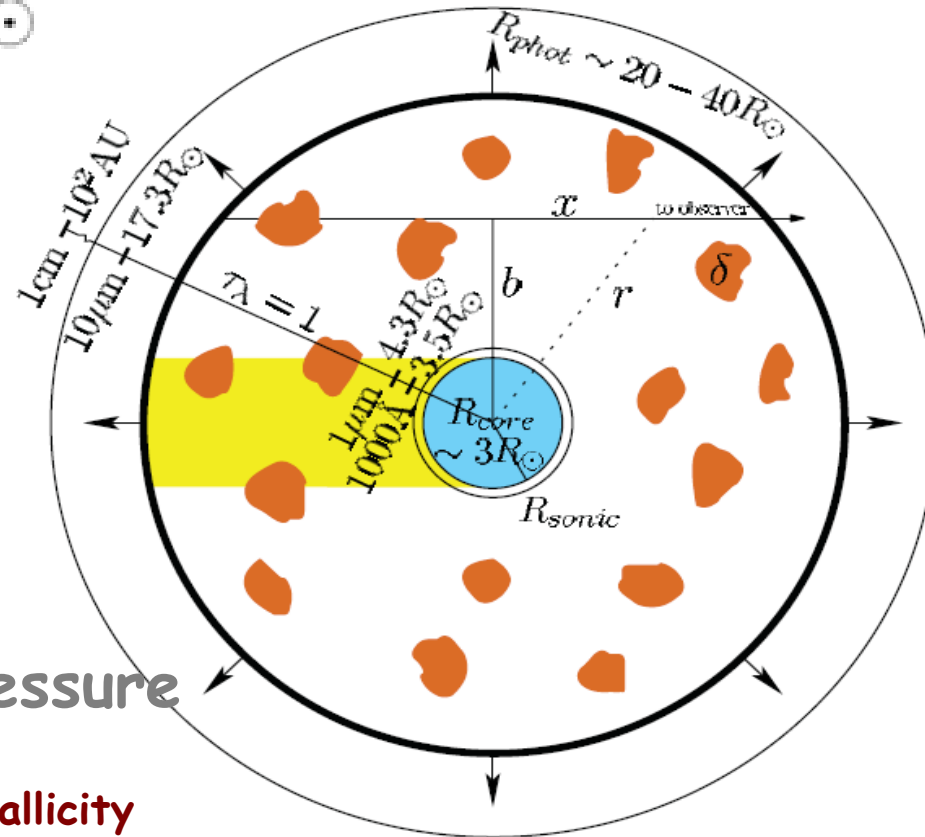
stellar rotation impact

Meynet 2007



$$\dot{M}_{\text{W-R}} \sim 10^{10} \dot{M}_{\odot}$$

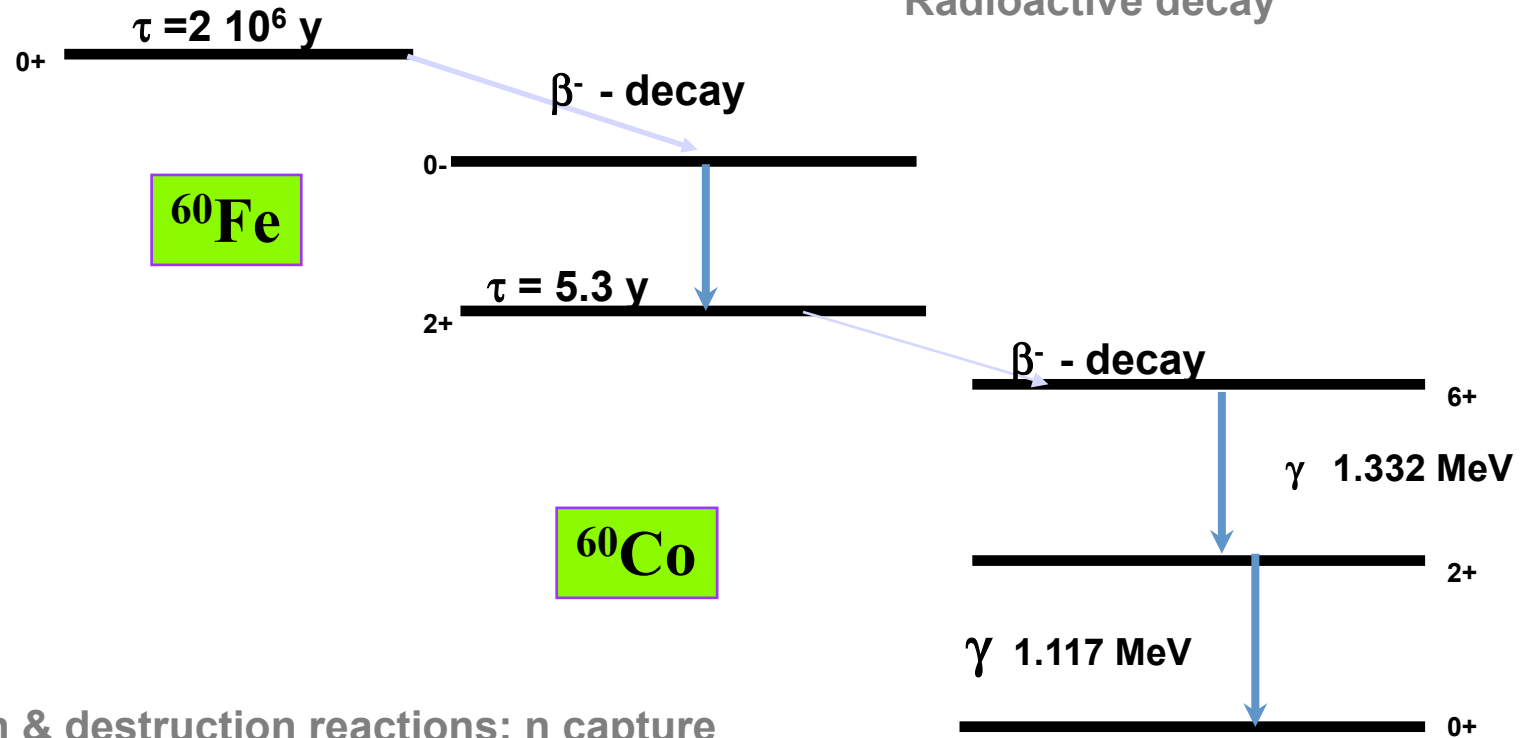
- $$10^{-5} \leq \dot{M} \leq 10^{-4} M_{\odot} \text{ yr}^{-1}$$
- $$v_{\infty} \sim \text{a few} \times 10^3 \text{ km s}^{-1}$$



- 👉 e.g. Hillier 1987, Heger & Langer 1996, Schmutz 1997, Smith & Houck 2005, Vink & Eldridge 2006, ...

^{60}Fe

Radioactive decay



Production & destruction reactions: n capture

Co55 17.53 h 7/2- EC	Co56 77.27 d 4+ EC	Co57 271.79 d 7/2- EC	Co58 70.82 d 2+ EC *	Co59 7/2- 100	Co60 5.2714 y 5+ *	Co61 1.650 h 7/2- *	Co62 1.50 m 2+ *	Co63 27.4 s (7/2)- *
Fe54 0+ 5.8	Fe55 2.73 y 3/2- EC	Fe56 0+ 91.72	Fe57 2.2	Fe58 0+ 0.28	Fe59 44.503 d 3/2- *	Fe60 1.5E+6 y 0+ *	Fe61 5.98 m 3/2- *	Fe62 68 s 0+ *
Mn53 3.74E+6 y 7/2- EC	Mn54 312.3 d 3+ EC, β^-	Mn55 5/2- 100	Mn56 2.5785 h 3+ *	Mn57 85.4 s 5/2- *	Mn58 3.0 s 0+ *	Mn59 4.6 s 3/2-, 5/2- *	Mn60 51 s 0+ *	Mn61 0.71 s (5/2-) *

^{60}Fe Synthesis: The relevant Nuclear Reactions



★ n Capture on
 ^{58}Fe , ^{59}Fe , ^{60}Fe

★ β Decay of $^{59,60}\text{Fe}$

Co55 17.53 h 7/2- EC	Co56 77.27 d 4+ EC	Co57 271.79 d 7/2- EC	Co58 70.82 d 2+ EC *	Co59 7/2- 100	Co60 5.2714 y 5+ *	Co61 1.650 h 7/2- *	Co62 1.50 m 2+ *	Co63 27.4 s (7/2)- β^-
Fe54 0+ 5.8	Fe55 2.73 y 3/2- EC	Fe56 0+ 91.72	Fe57 2+ 2.2	Fe58 0+ 0.28	Fe59 44.503 d 3/2- β^-	Fe60 1.5E+6 y 2/2- β^-	Fe61 5.98 m 3/2- β^-	Fe62 68 s 0+ β^-
Mn53 3.74E+6 y 7/2- EC	Mn54 312.3 d 3+ EC, β^-	Mn55 5/2- 100	Mn56 2.5785 h 3+ β^-	Mn57 85.4 s 5/2- β^-	Mn58 3.0 s 0+ β^-	Mn59 4.6 s 3/2-,5/2- β^-	Mn60 51 s 0+ *	Mn61 0.71 s (5/2)- β^-

★ Dependencies:

☞ n Density in Stellar Regions
of Interest: $^{22}\text{Ne}(a,n)^{25}\text{Mg}$

☞ T (\rightarrow β decay lifetimes)

^{60}Fe Synthesis: The relevant Nuclear Reactions

★ n Capture Rates of ^{58}Fe , ^{59}Fe , ^{60}Fe

☞ **measurements:**

- Notre Dame (Uberseder+)
- KIT, FRANZ (Reifarh+)

☞ **analyses in progress (2012+)**

Co55 17.53 h 7/2- EC	Co56 77.27 d 4+ EC	Co57 271.79 d 7/2- EC	Co58 70.82 d 2+ EC *	Co59 7/2- 100	Co60 5.2714 y 5+ *	Co61 1.650 h 7/2- *	Co62 1.50 m 2+ *	Co63 27.4 s (7/2)- β
Fe54 0+ 5.8	Fe55 2.73 y 3/2- EC	Fe56 0+ 91.72	Fe57 2.2	Fe58 0.28	Fe59 44.503 d 3/2- β	Fe60 1.5E+6 y 7/2- β	Fe61 5.98 m 3/2- β	Fe62 68 s 0+ β
Mn53 3.74E+6 y 7/2- EC	Mn54 312.3 d 3+ EC,β	Mn55 5/2- 100	Mn56 2.5785 h 3+ β	Mn57 85.4 s 5/2- β	Mn58 3.0 s 0+ β	Mn59 4.6 s 3/2-,5/2- β	Mn60 51 s 0+ β	Mn61 0.71 s (5/2)- β

★ ^{60}Fe Lifetime

☞ Rugel et al. 2009:

☞ Spallation-produced ^{60}Fe from Cu PSI p beam dump 590 MeV 12 yrs

☞ ^{60}Fe Determinations: ^{60}Co Appearance; AMS

☞ $\tau \sim 3.8 \text{ My} \pm 5\%$

– Kutschera et al. 1984: $\tau = 2.15 \pm 0.42 \text{ My}$

☞ **assessed?**

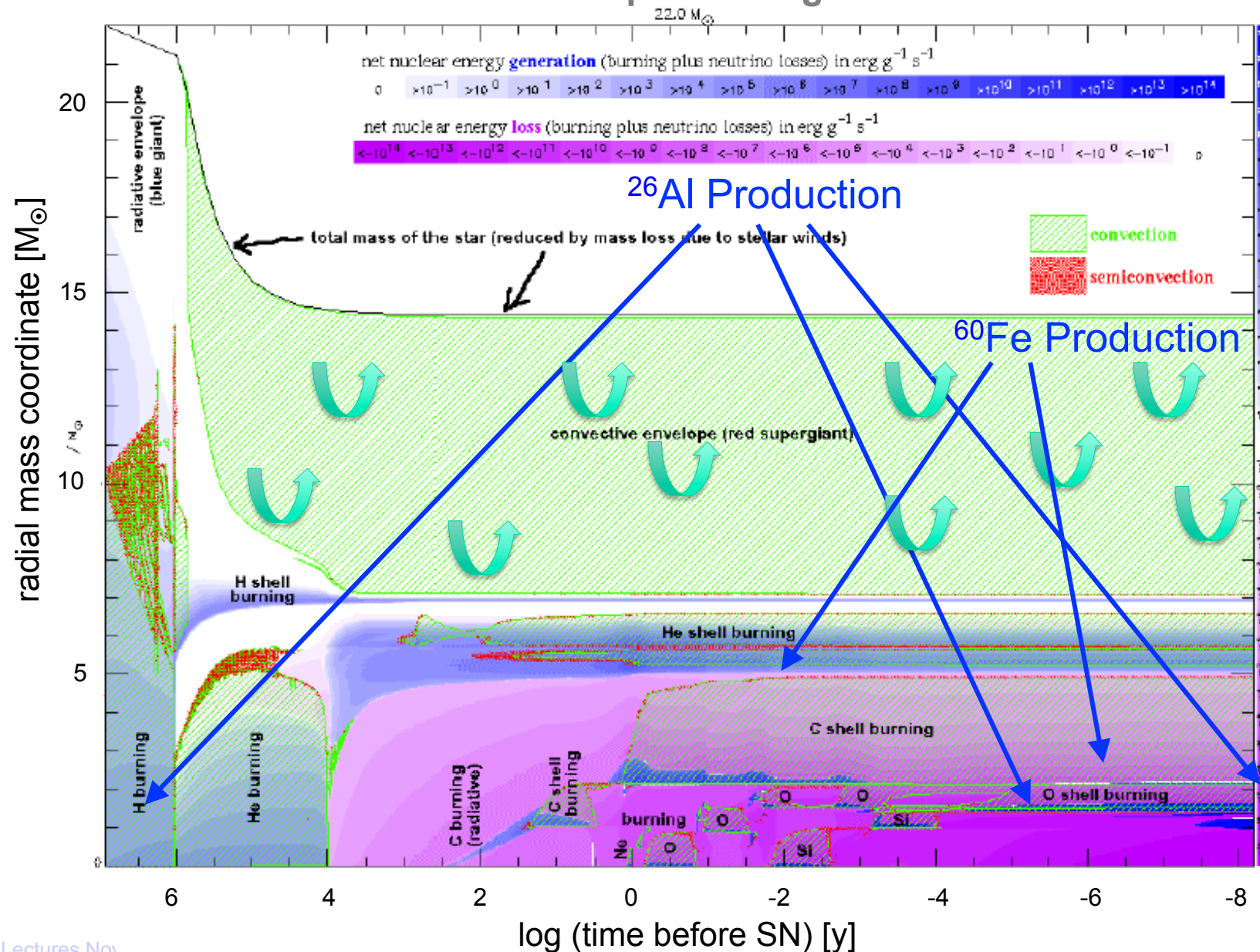
★ b Decay Lifetimes of $^{59,60}\text{Fe}$ $t_b(T)$

☞ decrease of $\tau_{\beta,59}$ at $T \sim 5 \cdot 10^8 \text{ K}$

☞ decrease of $\tau_{\beta,60}$ at $T \sim 4 \cdot 10^8 \text{ K}$

Nuclear Products as Diagnostics

- Nuclear Reaction Products from Specific Regions inside Massive Stars

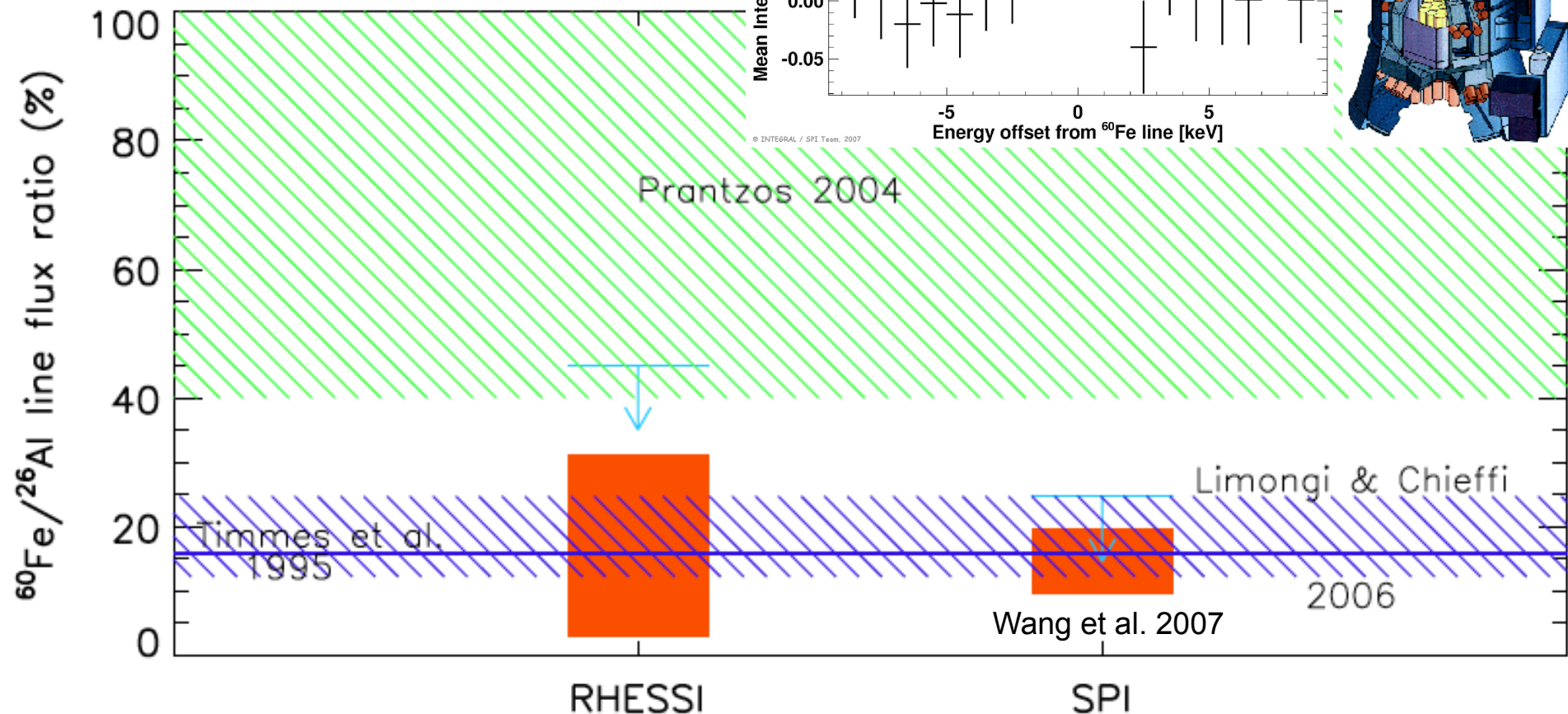
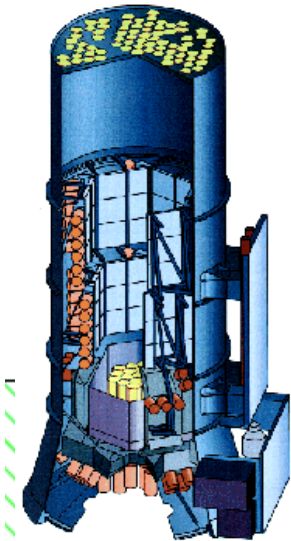
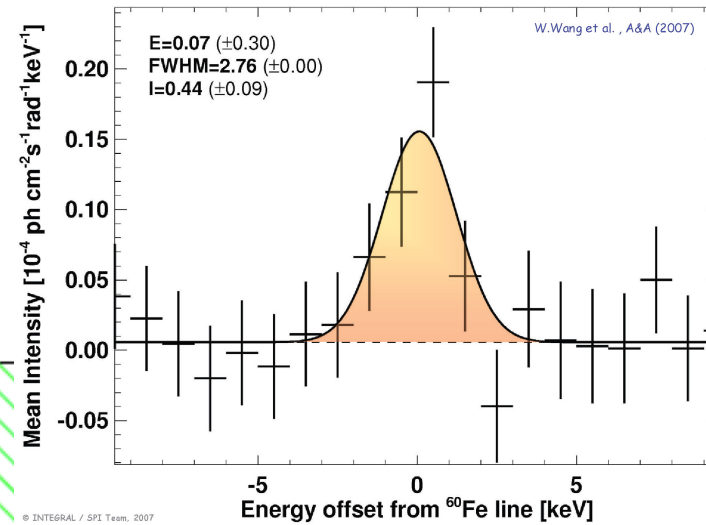


Nuclear Product Diagnostics: $^{60}\text{Fe}/^{26}\text{Al}$



- Measured Ratio
~Consistent

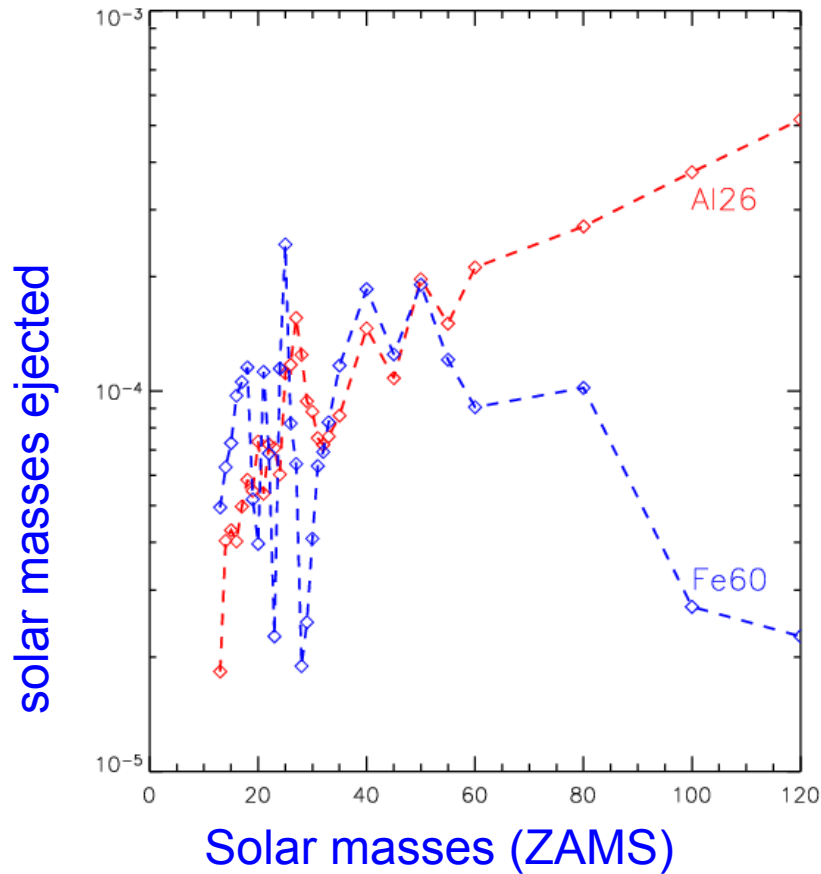
👉 Fortuitous??



Modeling Massive-Star Nucleosynthesis

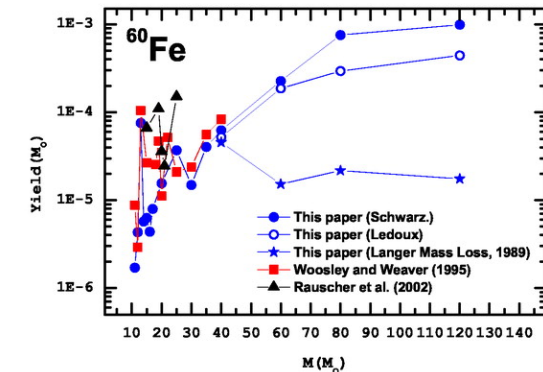
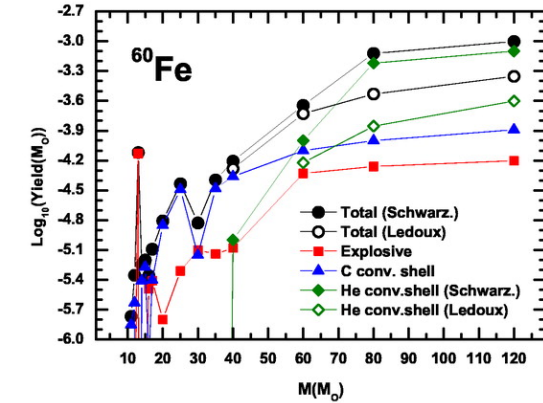


survey 2005 / Woosley, priv.comm, PRL'07:



Limongi & Chieffi 2006:

- ★ MS Evolution through SN
- ★ Test Various Convection & Mixing & Mass Loss Models
- ★ High-End Masses Very Variable for ^{60}Fe
- ★ Agree with Gamma-Ray Constraints for Latest Models and $M_{\text{upper}}=80M_{\odot}$



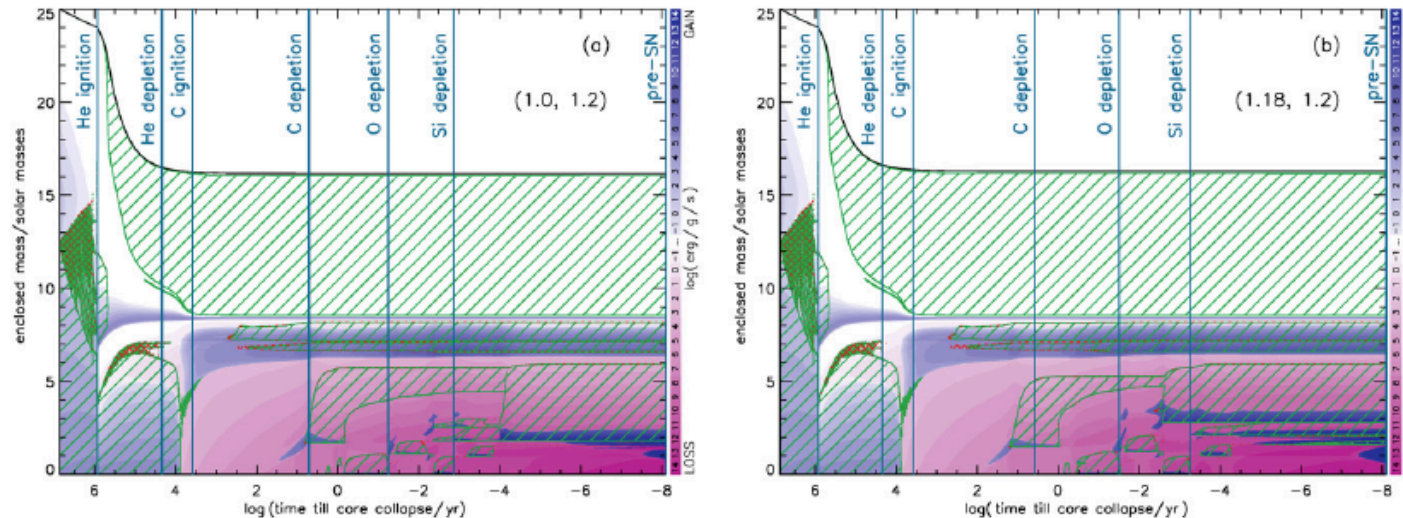
$$\left(\frac{{}^{60}\text{Fe}}{{}^{26}\text{Al}} \right)_{10-120} = 0.95 \quad \text{Goal:} \quad \left(\frac{{}^{60}\text{Fe}}{{}^{26}\text{Al}} \right) = 0.29$$

IMF: $\Gamma=-1.35$

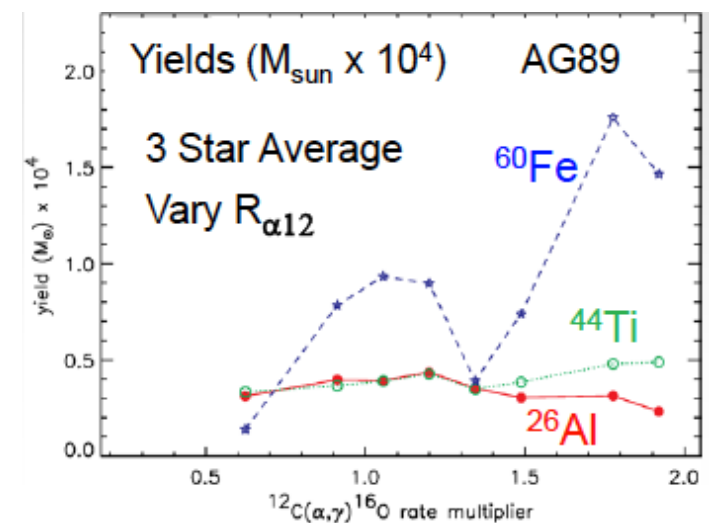
Woosley & Heger 2007:

- ★ He Core Evolution through SN
- ★ Including n Process
- ★ Corrected Rates vs. Rauscher et al. 2002

^{60}Fe from Massive Stars



- Yields are Uncertain from
 - ★ Nuclear Reactions in ^{60}Fe Production & Destruction
 - ★ Supernova Structure:
 - ☞ Late Shell Merging? → Pre-SN Productions
 - ☞ Stellar Evolution Dependence on of 3α and $^{12}\text{C}(\alpha, \gamma)$ Rates (Tur+2010)
 - ★ Contributing Stellar Masses:
 - ☞ Stars above $\sim 40 M_{\odot}$ could form BHs directly (Brown & Woosley 2013)



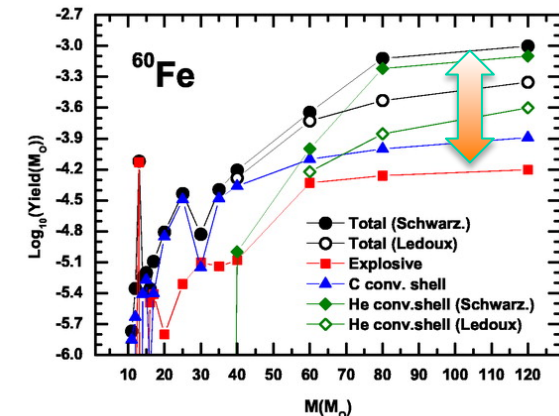
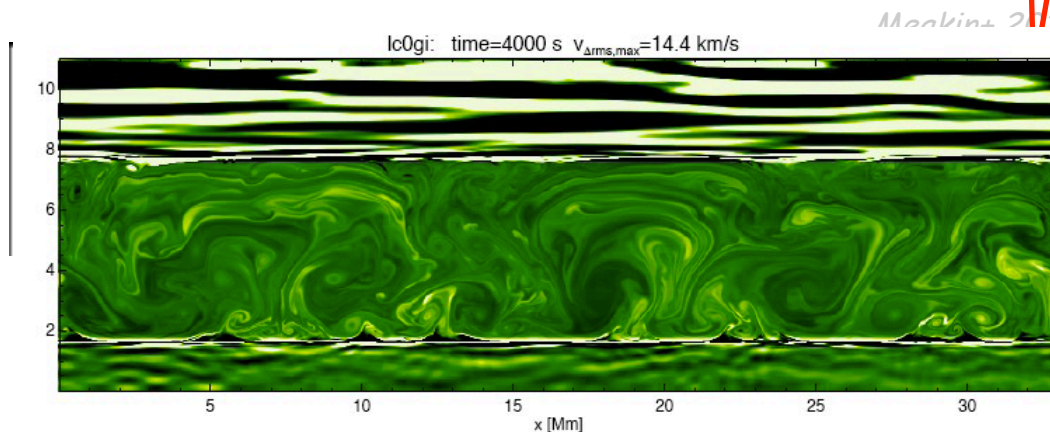
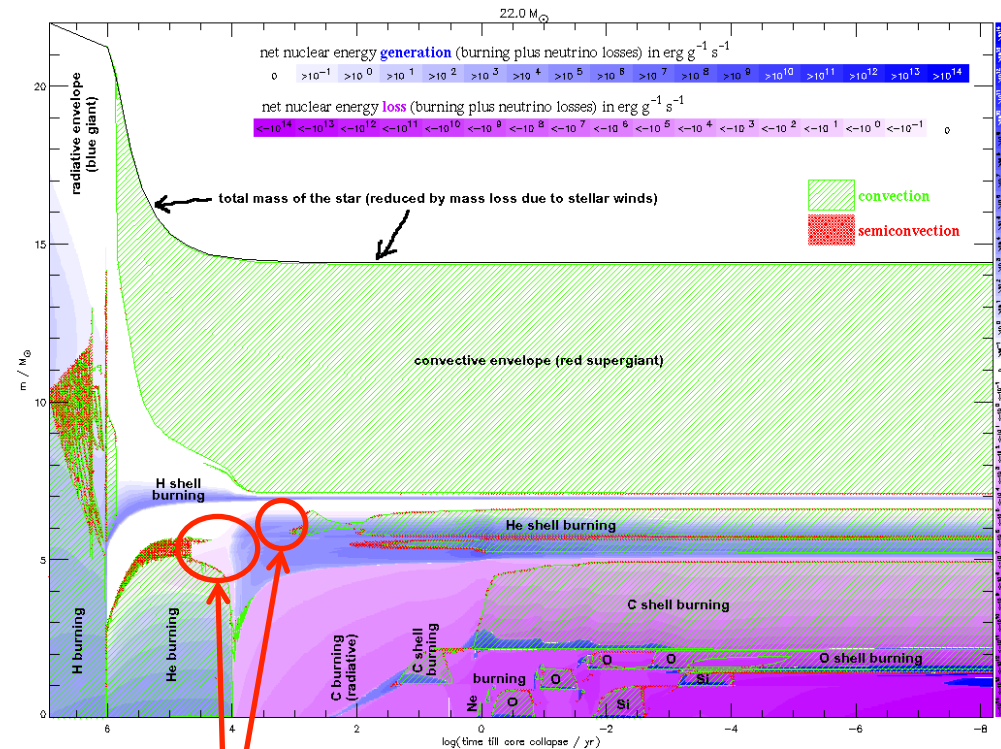
Massive-Star Structure: Convection Issues



★ How Does Convective Zone Transit into Stable (radiative) Zone?

★ 3D Simulations Illustrate

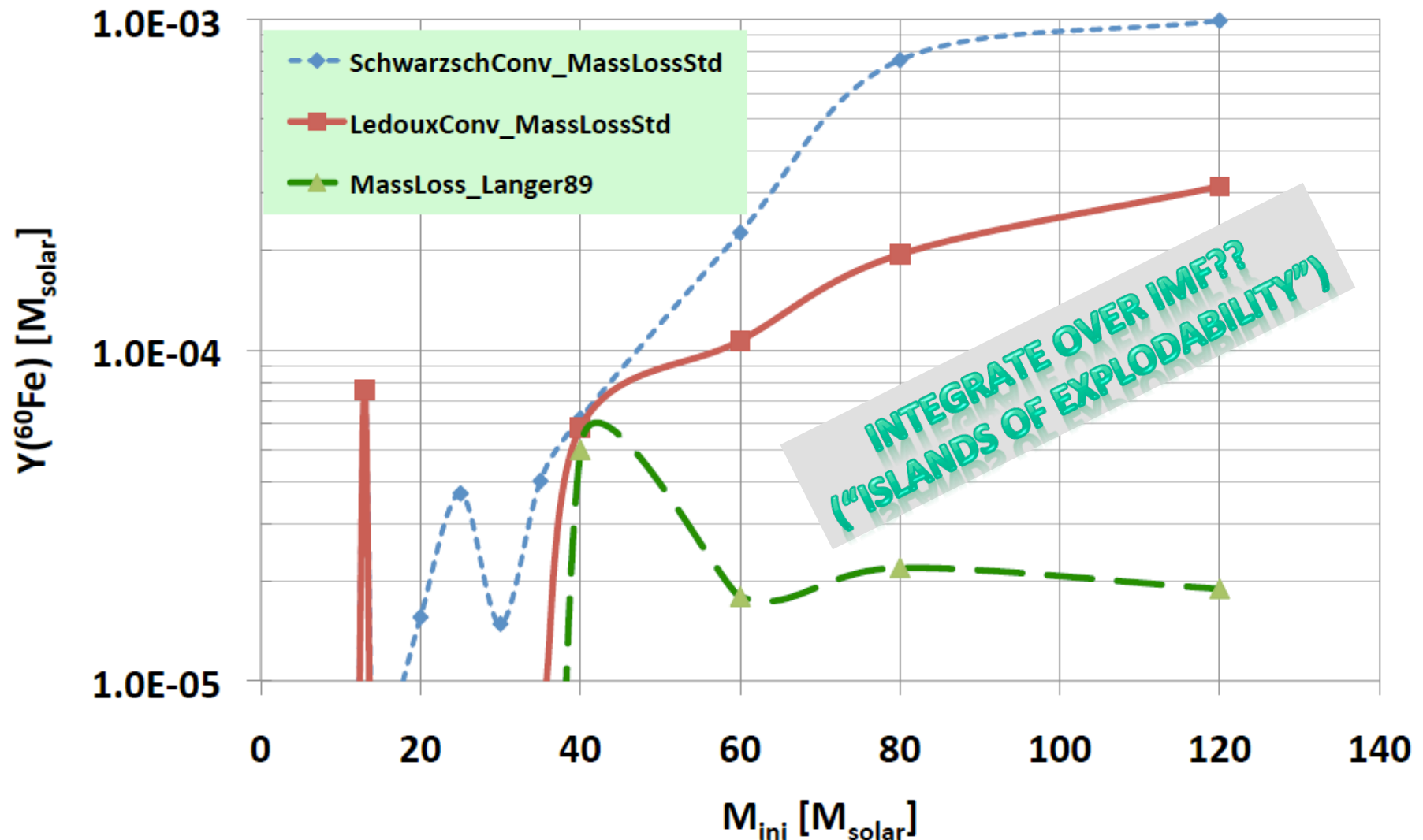
- ➡ The Inadequacy of “Mixing-Length” Modeling
- ➡ Details of “Semiconvection”, “Overshooting” and other Empirical Corrections
- ➡ How e.g. Stellar Rotation Leads to 3D Mixing Processes



➡ Affects Isotopic Yields (e.g. ^{60}Fe)

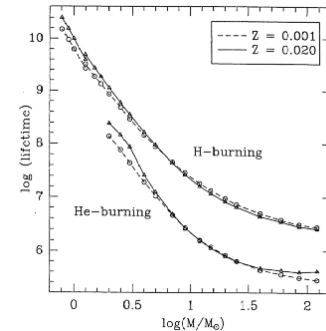
Yield of ^{60}Fe : Sensitive to Model Issues

★ Model Parameters Have Major Impact on Total Yield



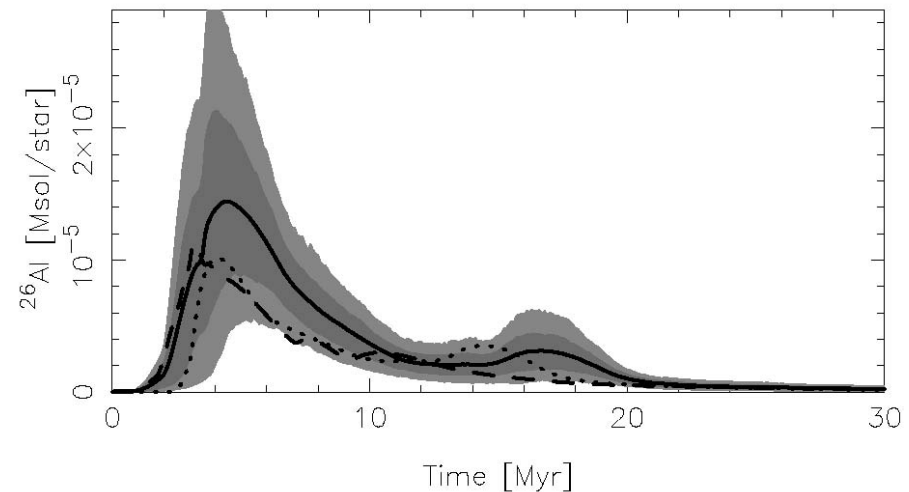
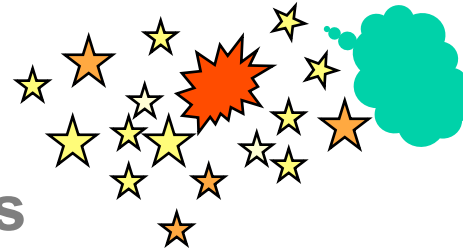
- Implement Known Massive-Star Properties

- ★ Stellar Evolution Phases and their Durations
- ★ Characteristic Emissions in Radiation and Winds



- Sample a Group of Stars
→ Assemble Group Properties

- ★ Time Profiles of Characteristic Emissions
- ★ Statistical Variations

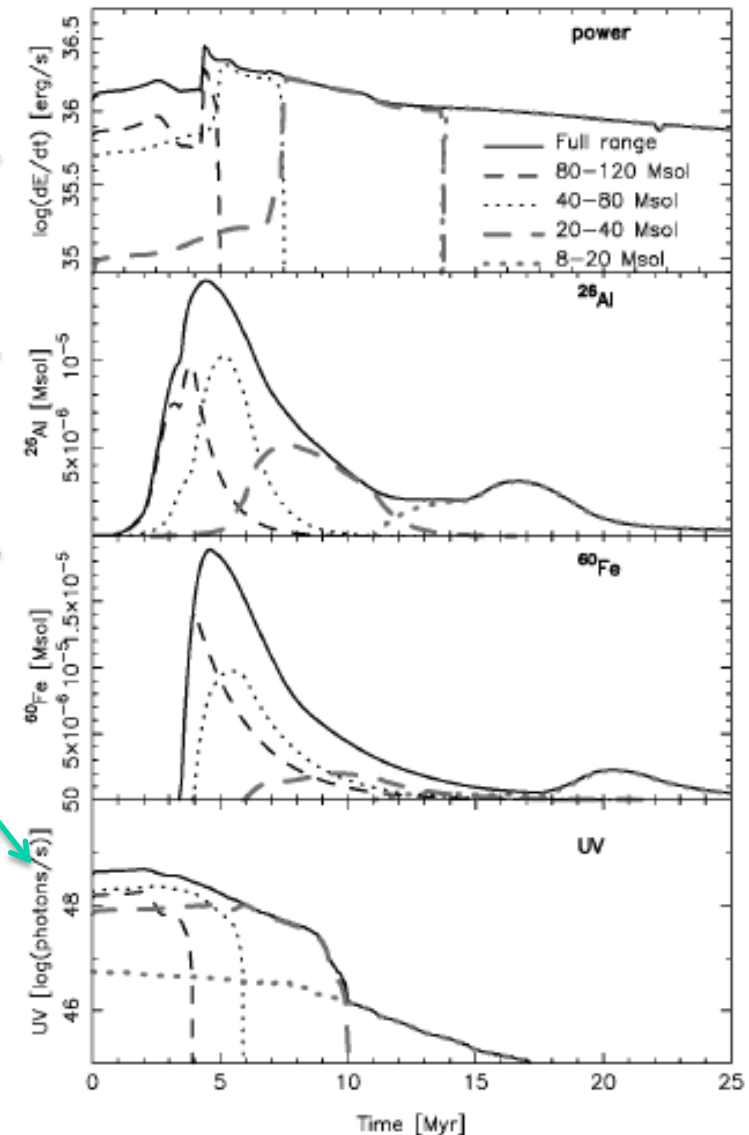


“Outputs” from Massive Star Groups



Voss R., et al., 2009

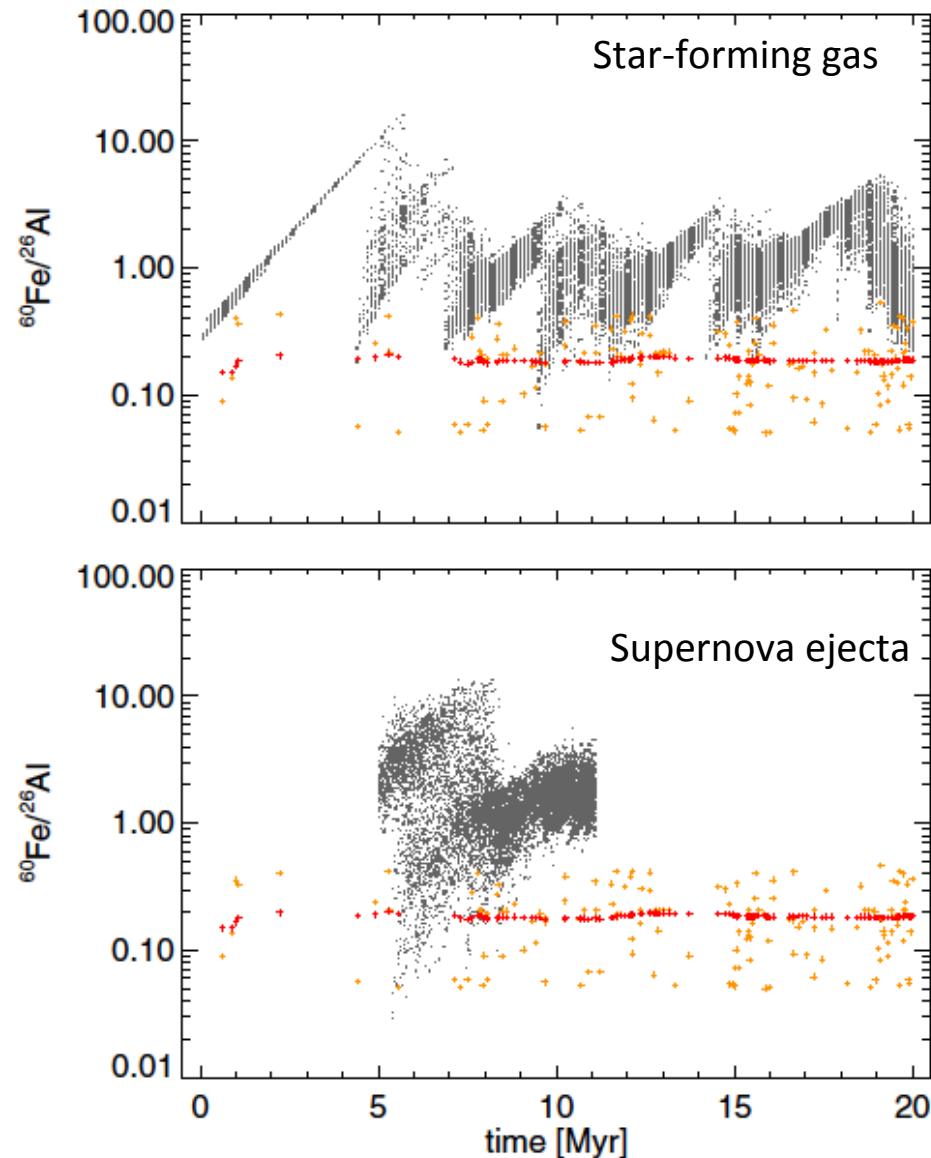
- Massive stars and their supernovae generate:
 - ★ Winds and Explosions
 - ★ Nucleosynthesis Ejecta
 - ★ Ionizing Radiation
- Observational Constraints from
 - ★ Star Counts
 - ★ ISM Cavities
 - ★ Free-Electron Emission
 - ★ Radioactive Ejecta



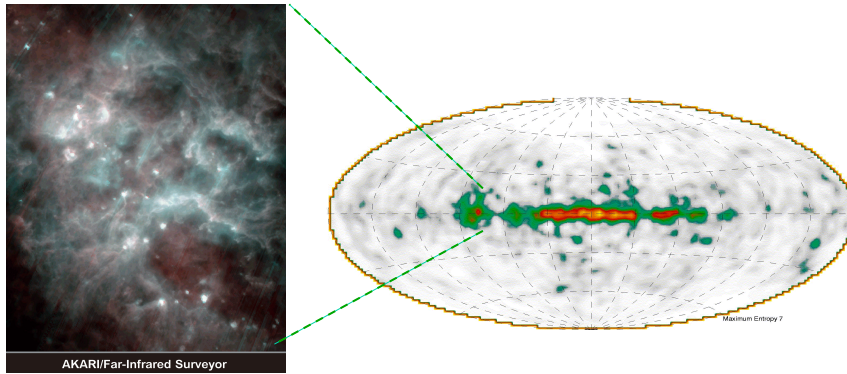
$^{60}\text{Fe}/^{26}\text{Al}$: Expectations from stars as they form and explode



- Hydrodynamical Simulations of a Giant Molecular Cloud's Evolution
 → Stars, SNe, Ejecta Flows and Feedback
 » *Vasileiadis, Nordlund, and Bizzarro 2013*



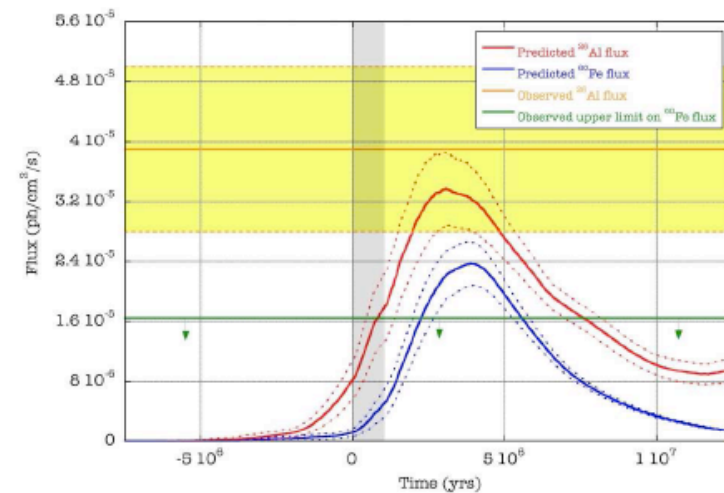
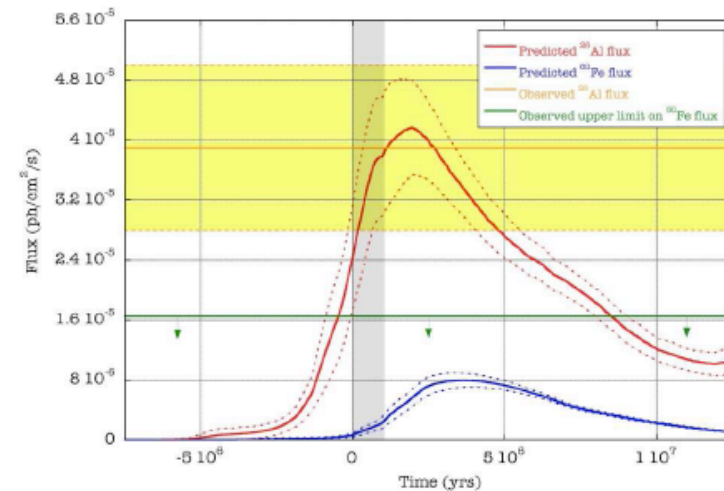
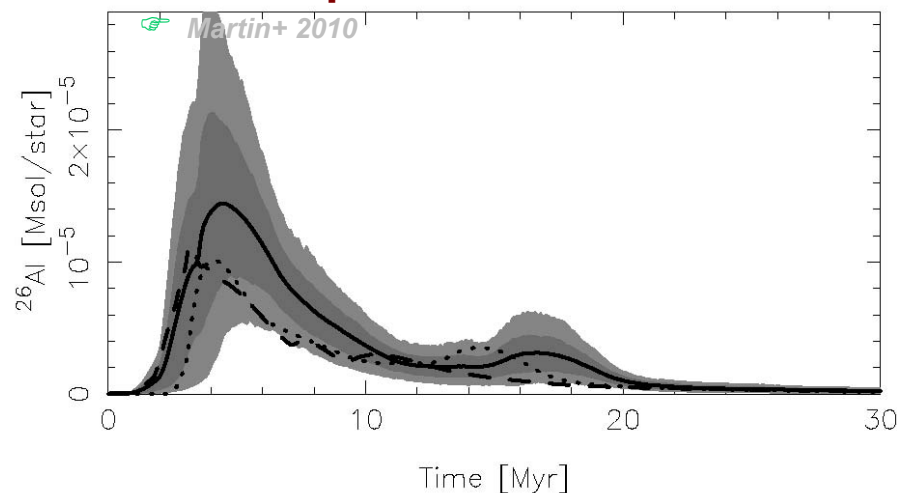
Testing our Models: Cygnus at its Specific Age and Metallicity



★ Population Synthesis: Application to Cygnus Region

👉 Models for Solar Metallicity
~OK

👉 If Lower Metallicity:
Underprediction?

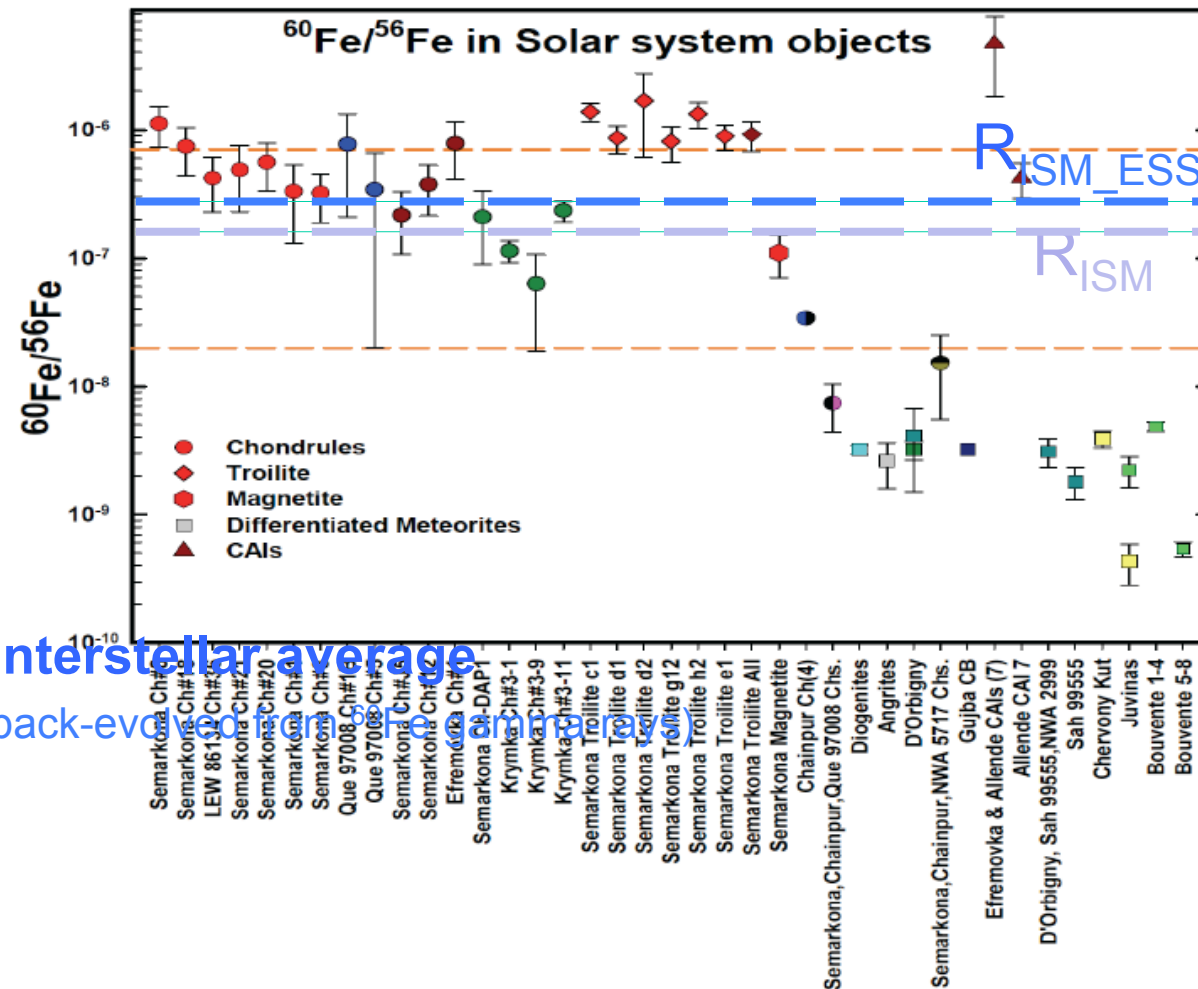


^{60}Fe in the Early Solar System

★ Measurements from Early Condensated Bodies:

👉 Initial $^{60}\text{Fe}/^{56}\text{Fe}$ ratios uncertain between few 10^{-7} and $<10^{-8}$

Mishra+2013



★ Could be ~ interstellar average
($R_{\text{ISM_ESS}}$, back-evolved interstellar average)

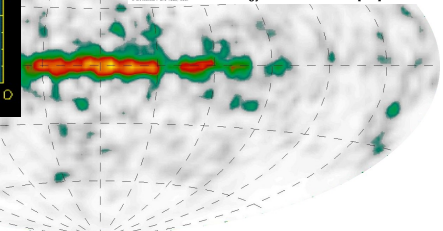
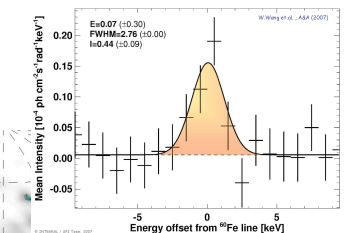
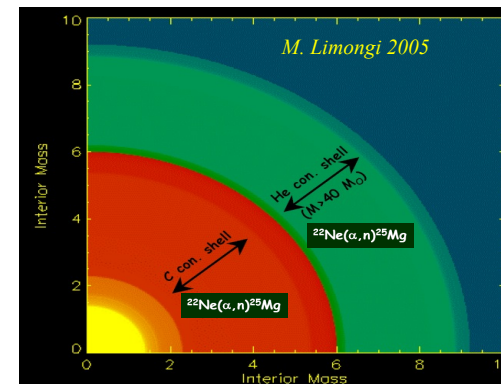
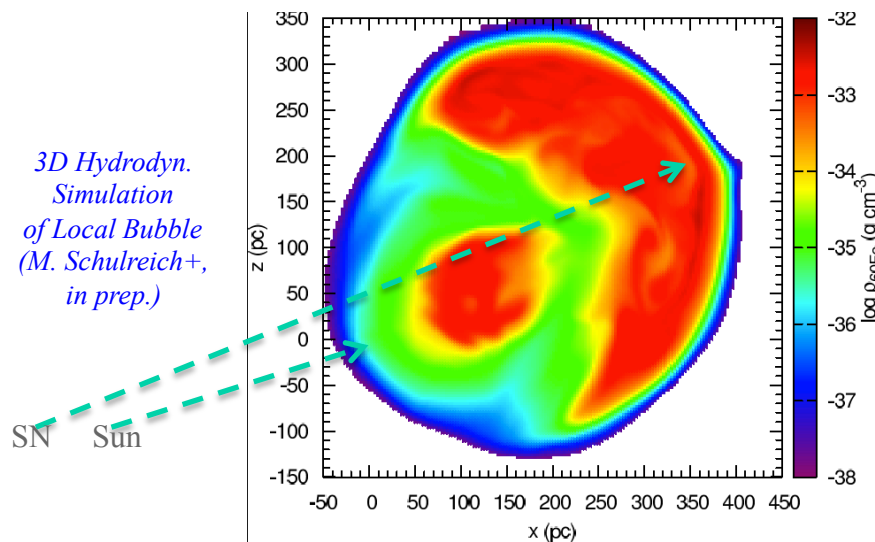
Understanding Measurements of SN Ejecta



- ^{60}Fe
 - ★ Clearly Seen in Oceanfloor Sample (and Galaxy-wide)
 - ★ Nuclear Physics?? (b decay, n capture)
 - ★ Massive-Star Envelope Models?? (Shell Burning & Mixing)
 - ★ SN Ejecta Transport at ~10pc Scale??

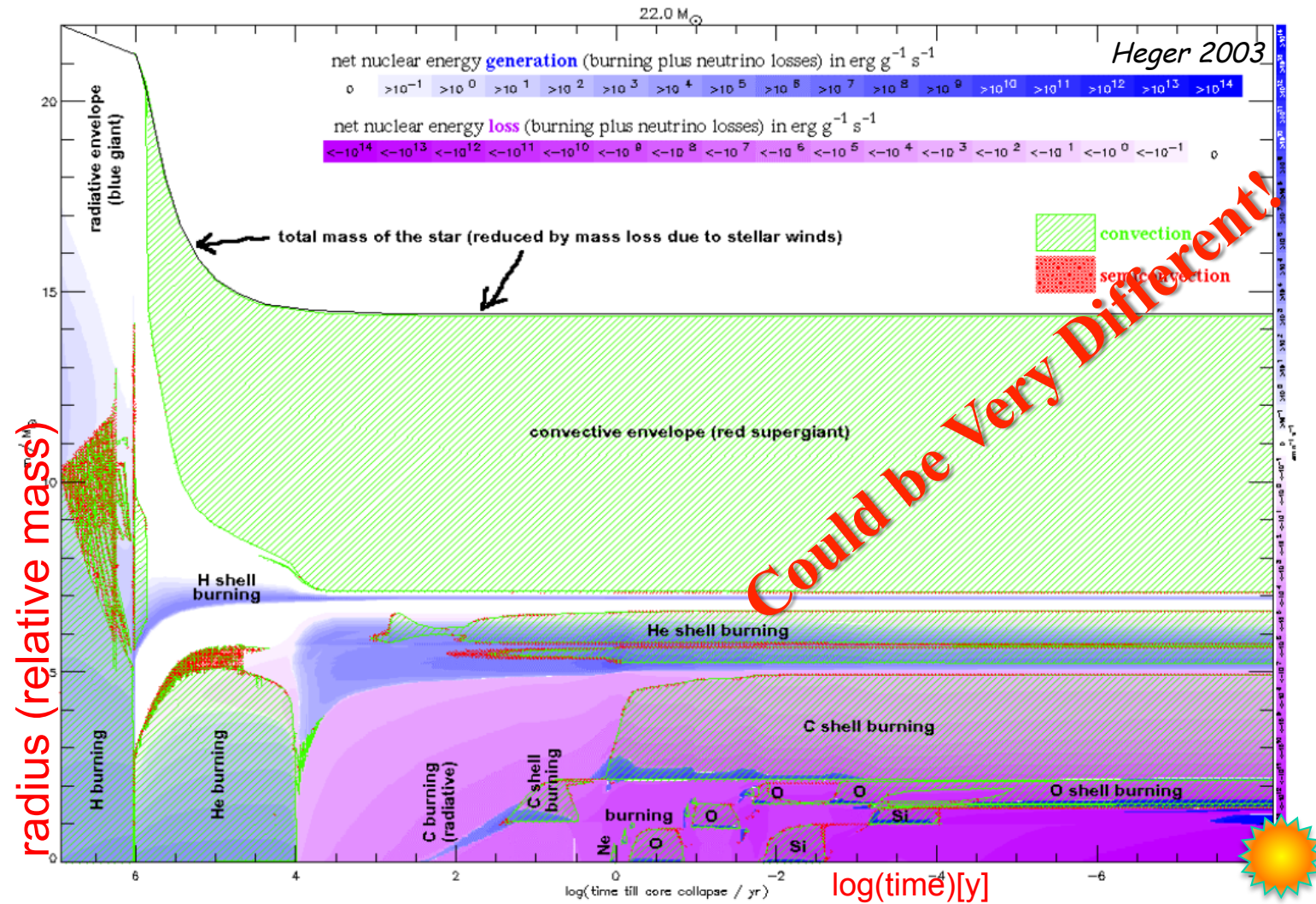


Co55 17.53 h 7/2- EC	Co56 77.27 d 4+ EC	Co57 271.79 d 7/2- EC	Co58 70.82 d 2+ EC *	Co59 7/2- 100	Co60 5.2714 y 5+ *	Co61 1.650 h 7/2- *	Co62 1.50 m 2+ *	Co63 27.4 s (7/2)- *
Fe54 0+ 5.8	Fe55 2.73 y 3/2- EC	Fe56 0+ 91.72	Fe57 2+ 2.2	Fe58 0+ 0.28	Fe59 44.503 d 3/2- *	Fe60 1.5E+6 y 2+ β-	Fe61 5.98 m 5/2- β-	Fe62 68 s 0+ β-
Mn53 3.74E+6 y 7/2- EC	Mn54 312.3 d 3+ EC, β-	Mn55 5/2- 100	Mn56 2.5785 h 3+ β-	Mn57 85.4 s 5/2- β-	Mn58 3.0 s 0+ *	Mn59 4.6 s 3/2-, 5/2- β-	Mn60 51 s 0+ *	Mn61 0.71 s (5/2)- β-



Following Stellar Evolution

☆ The “Kippenhahn” Diagram:



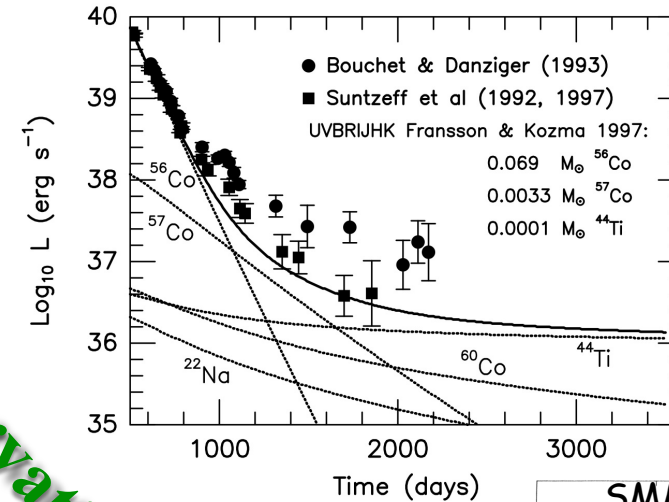
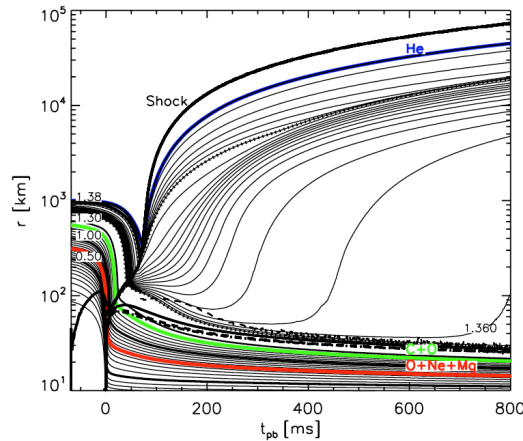
Aspects of a Core-Collapse Supernova



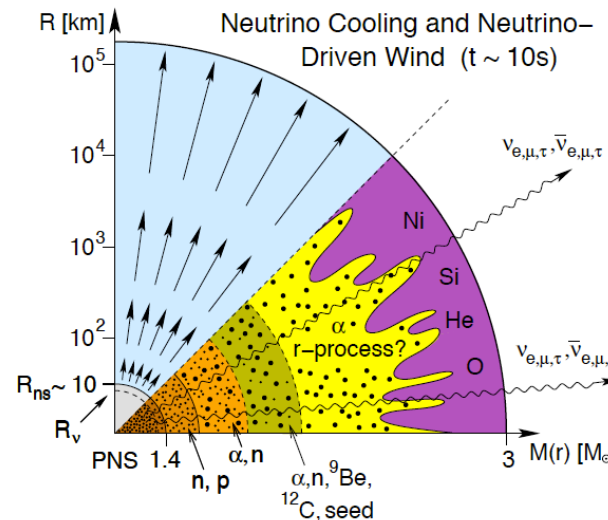
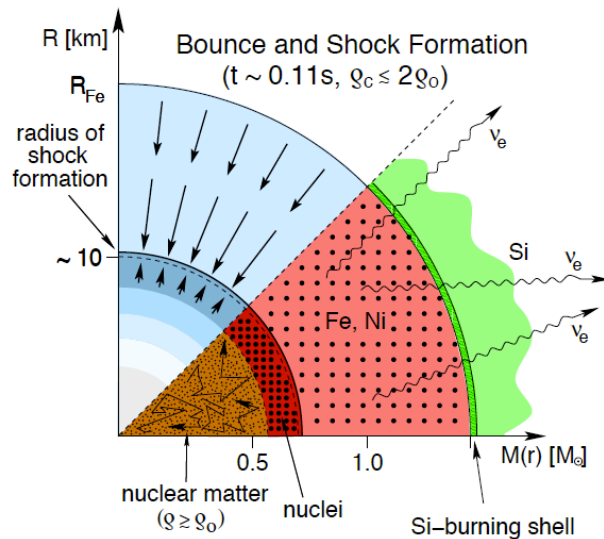
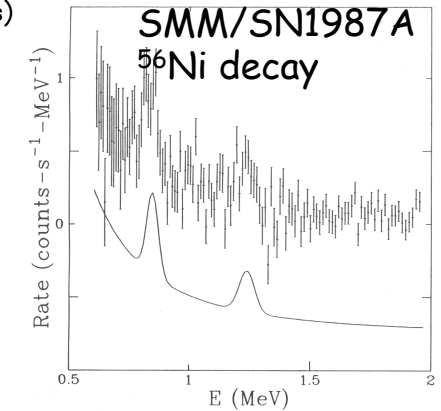
- Nuclear Energy Conversions +...

- ★ Dynamics of Explosions

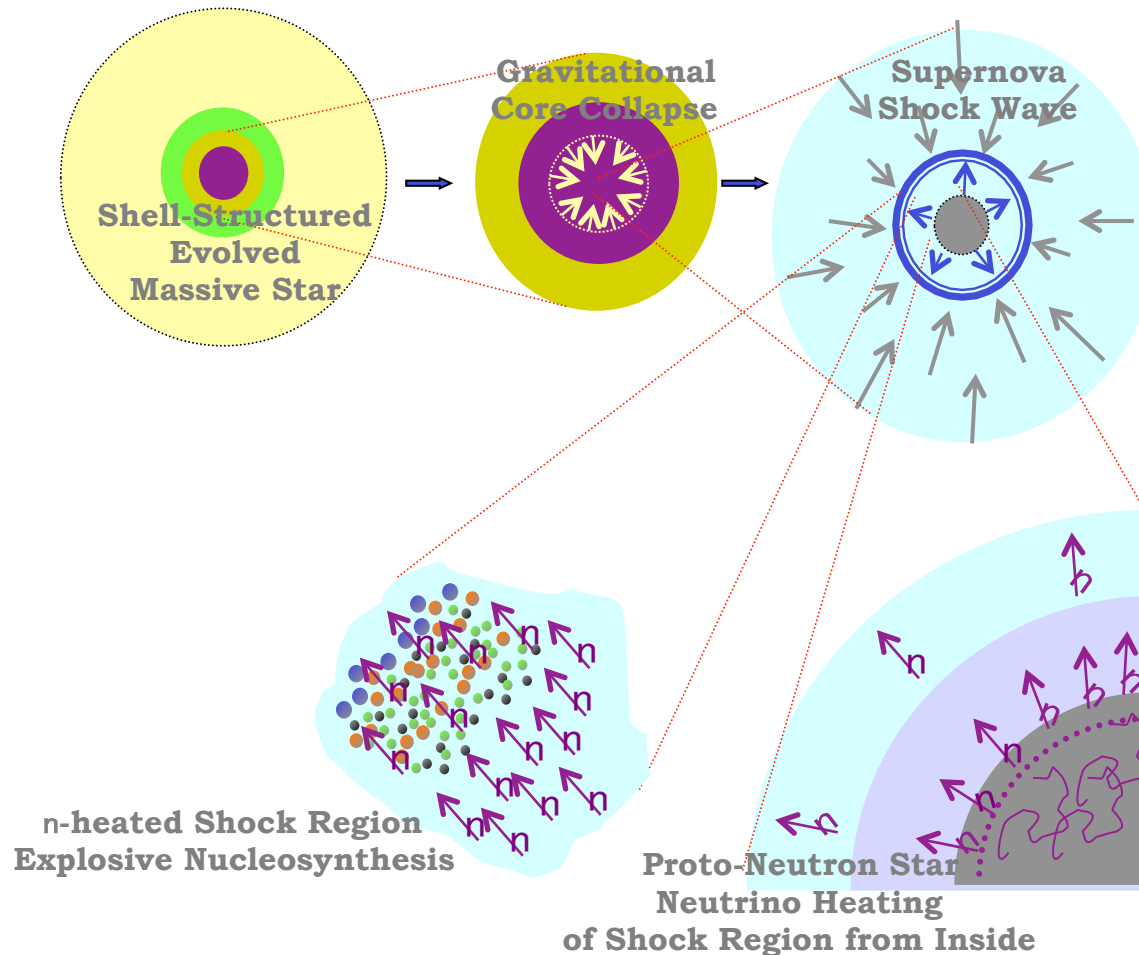
- ★ Structure of Stars



Observations
Models



Core Collapse-Supernovae: The Model



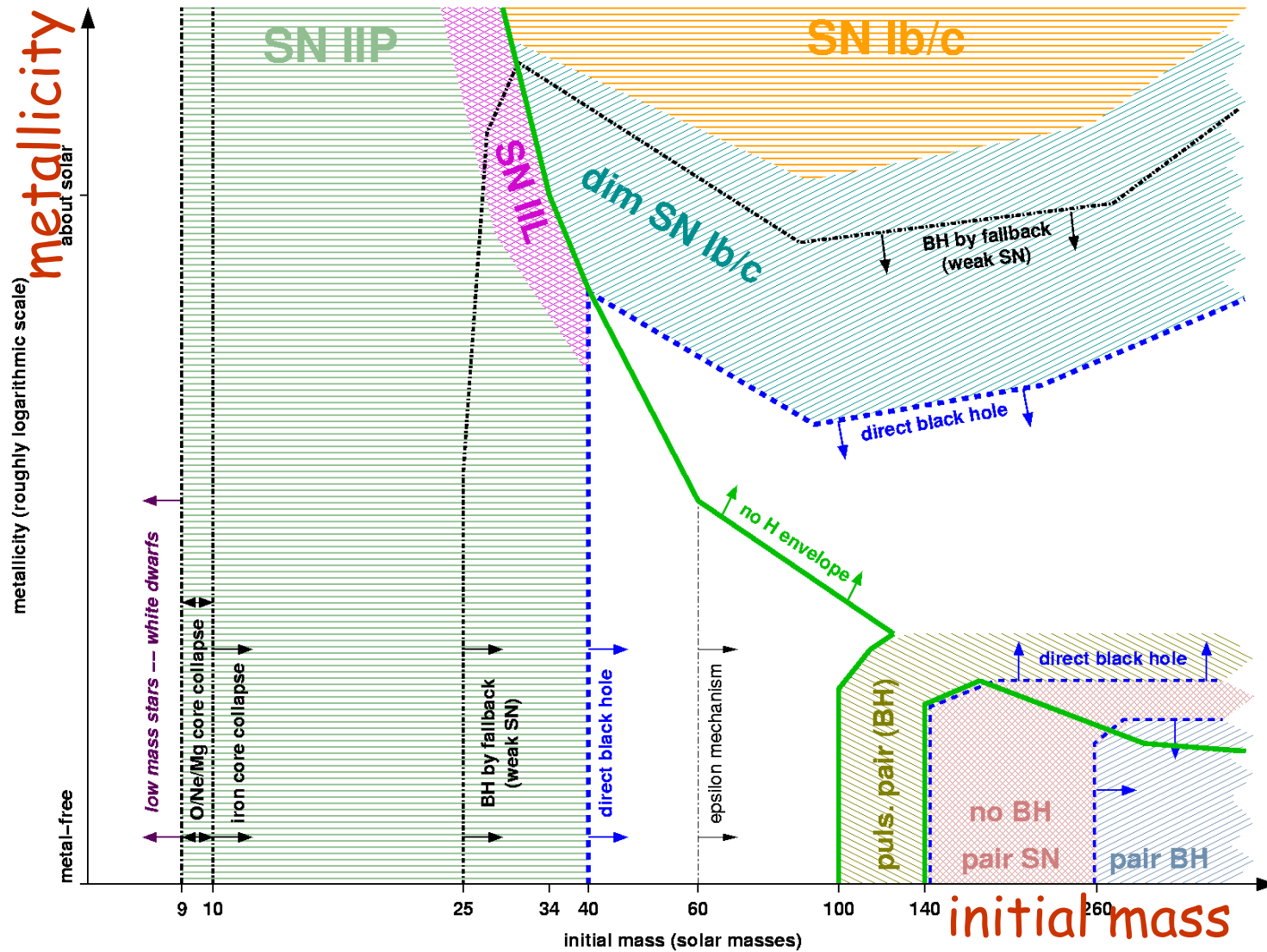
Empirical /
Parametrized
Models for Explosion
(Explosion Energy,
Mass Cut)

Nuclear Physics:

- n Luminosities
- PNS EoS,
Pasta Phases
- Nucleosynthesis
- Shock Region
- Explosive

- Explosion Mechanism = Competition Between Infall and Neutrino Heating
- 3D-Effects Important for Energy Budget AND Nucleosynthesis

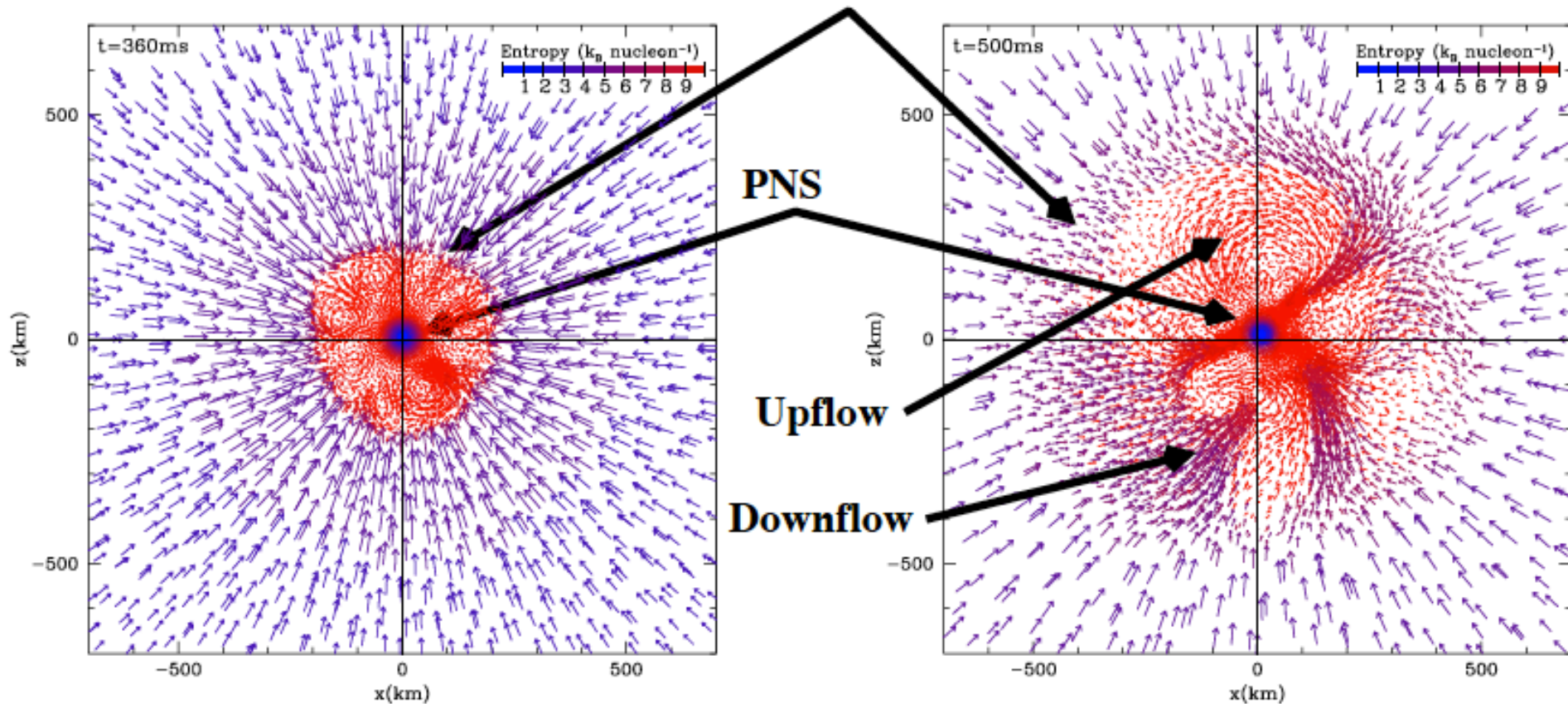
Stellar Evolution and Supernova Types



- Heger, Chieffi, Limongi, Woosley ... et al.

Inner Regions of ccSNe

- Simultaneous Inward and Outward Gas Flows

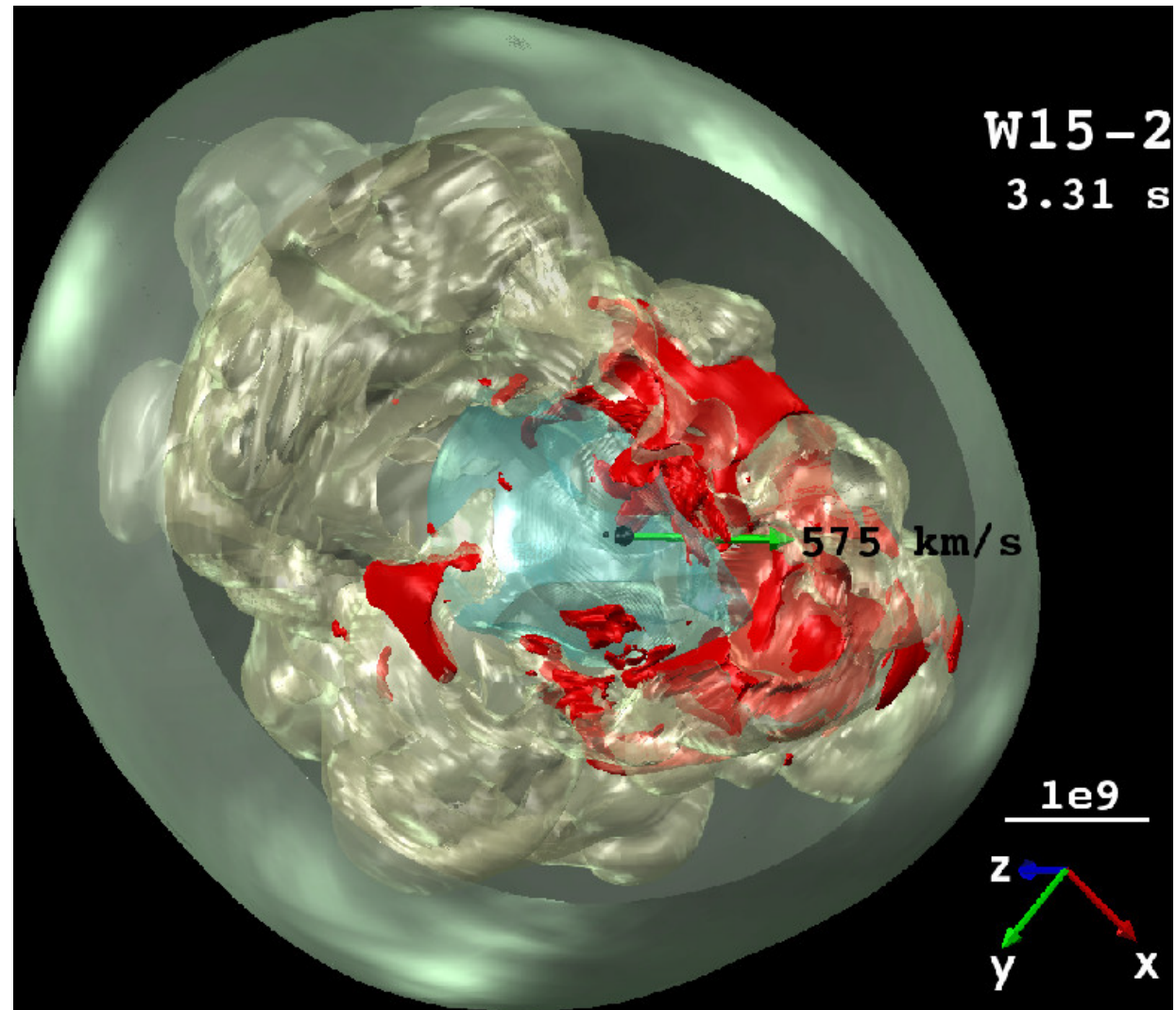
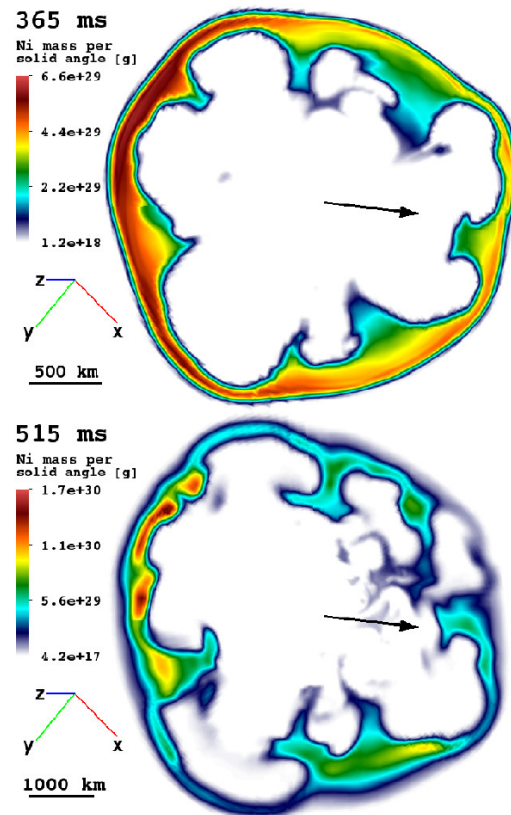


👉 e.g. Fryer et al. 2008; ref. Ewald Müller, this conference

Simulating a Core-Collapse SN in 3D

★ Asymmetric Explosions

- ☞ **NS Kick ~few 100 km/s, with inner ejecta towards opposite direction in slow clumps**
 - e.g. Wongwathanarath, Janka, & Müller 2012



^{44}Ti Ejecta Velocities

★ High-Energy Line Not Seen with SPI

☞ Velocity-Broadened, → Disappearing in Bgd

★ Estimate Doppler Broadening:

☞ Astrophysical Line Width > 3.2 keV
→ 500 km s^{-1} lower velocity limit

☞ *Martin et al. 2009*

★ ^{44}Ti Ejecta from Turbulent Zones Well Outside Mass Cut

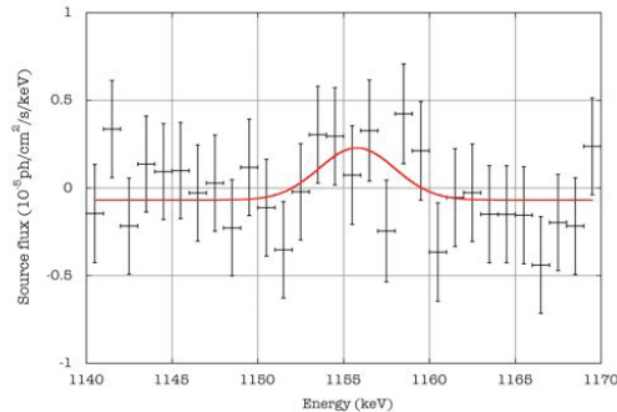
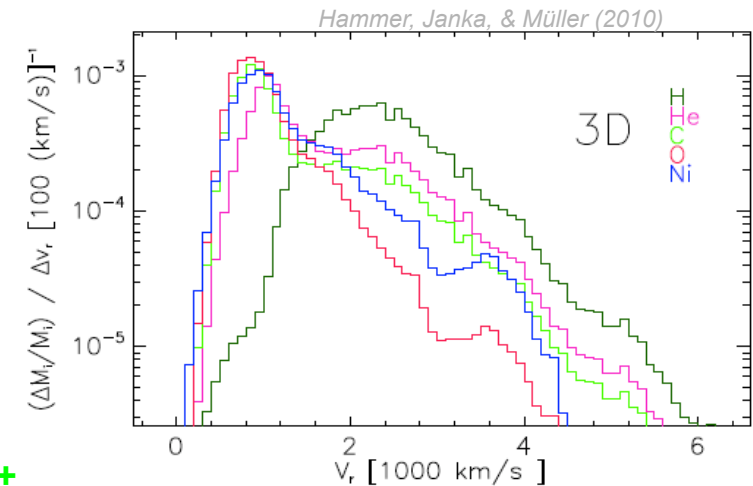
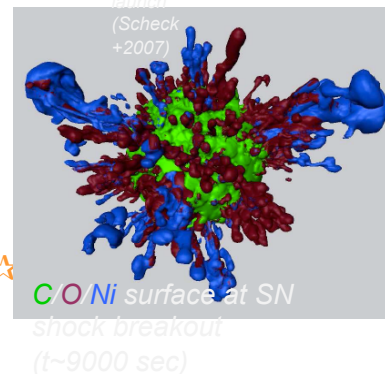
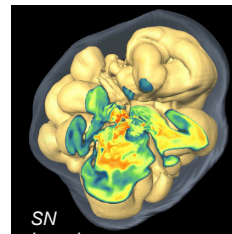
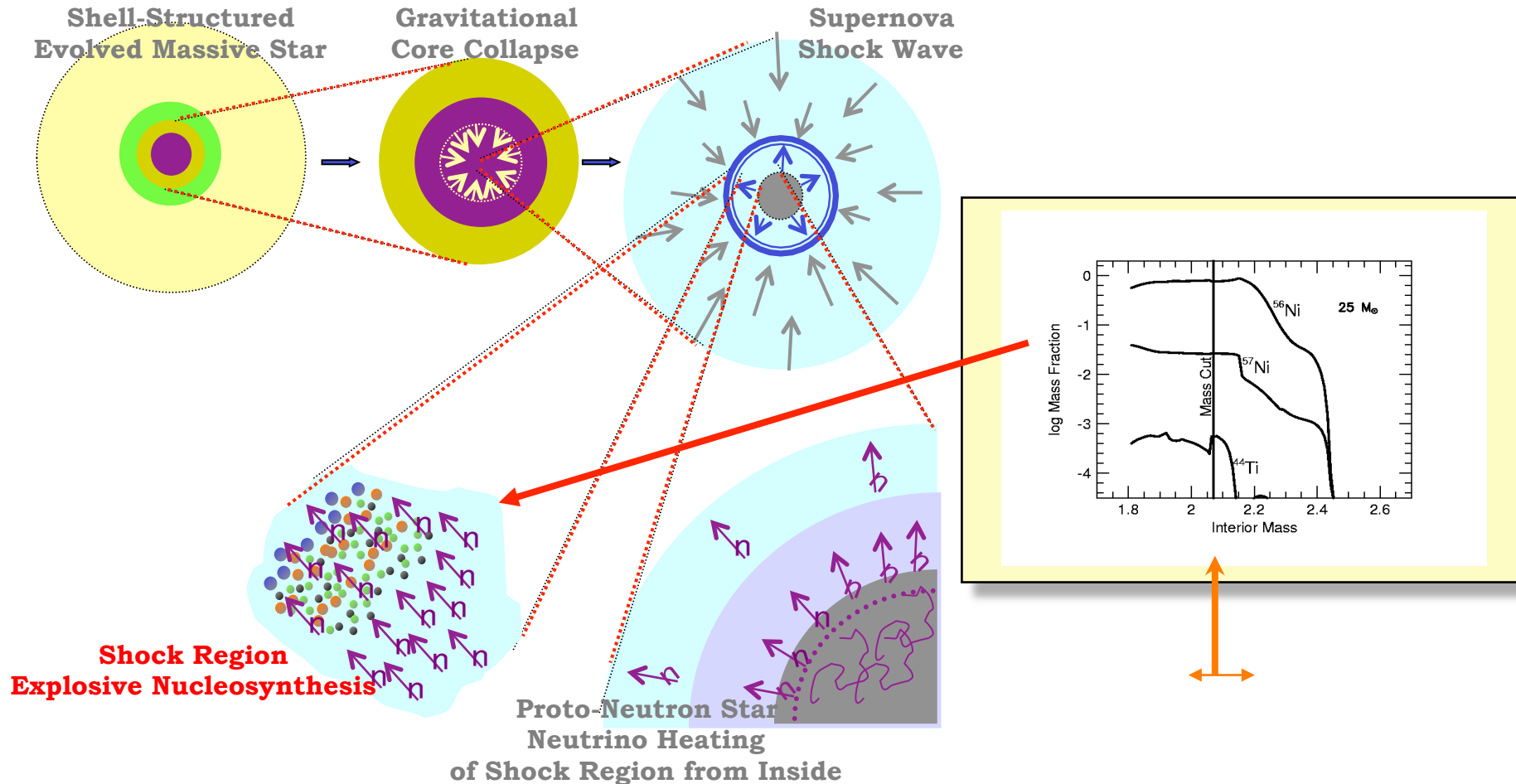


Fig. 4. Cassiopeia A spectrum at 1157.0 keV combining SE and ME2; red solid curve is the fit of a Gaussian shape.



Nucleosynthesis in CC-Supernove, and ^{44}Ti



- ^{44}Ti Produced at $r < 10^3$ km from a-rich Freeze-Out,
 \Rightarrow Unique Probe (+Ni Isotopes)

^{44}Ti γ -rays from Cas A

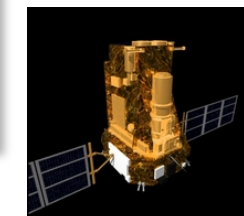
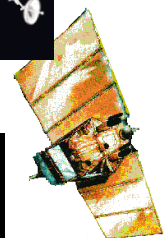
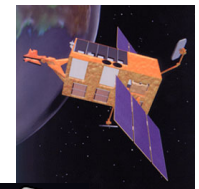
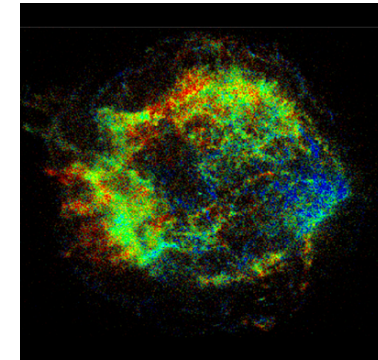
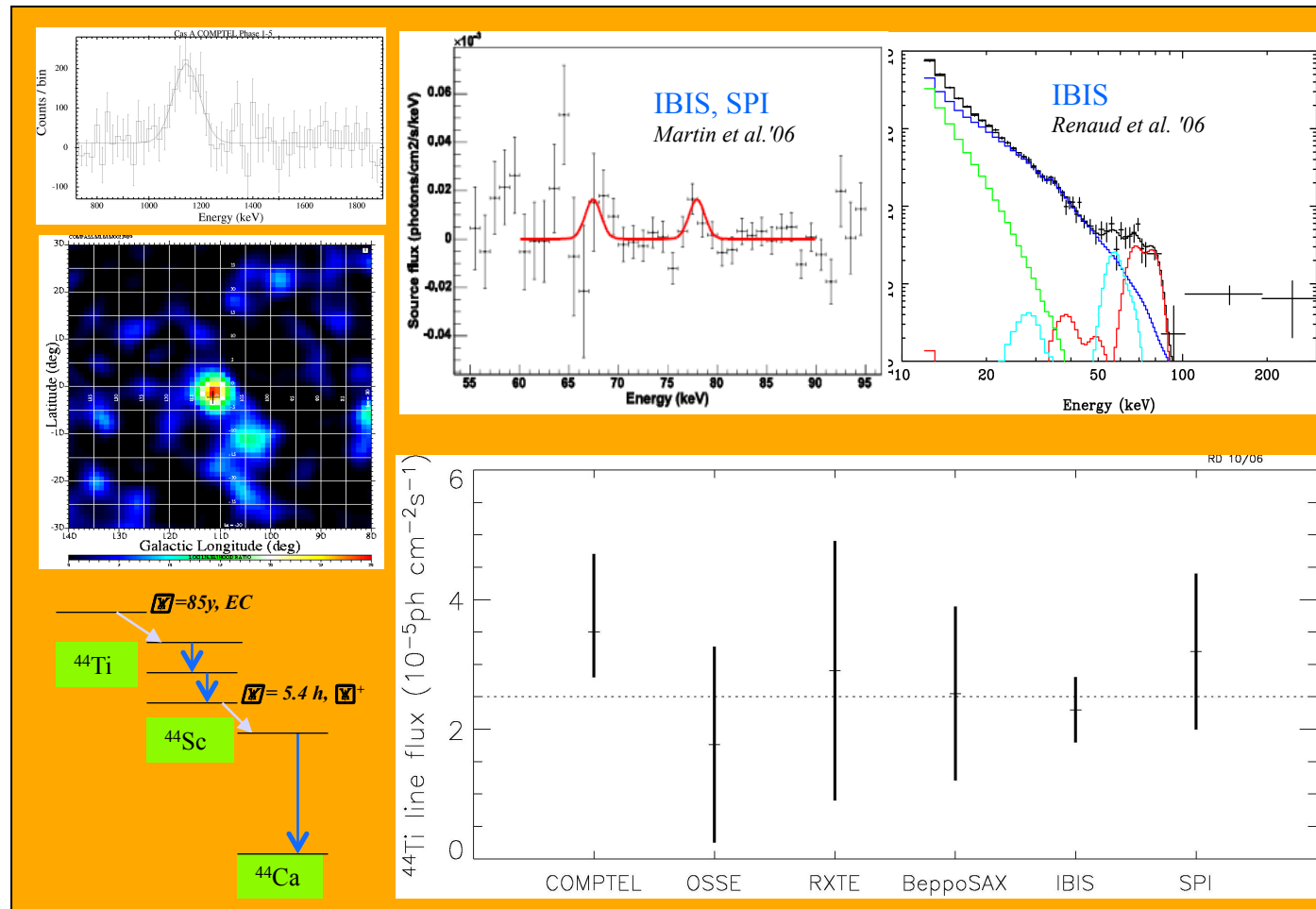


$t=85\text{y}$ (Ahmad et al. 2006)

89 y

$^{44}\text{Ti} \rightarrow ^{44}\text{Sc}^* \rightarrow ^{44}\text{Ca}^* + e^+$

78, 68; 1157



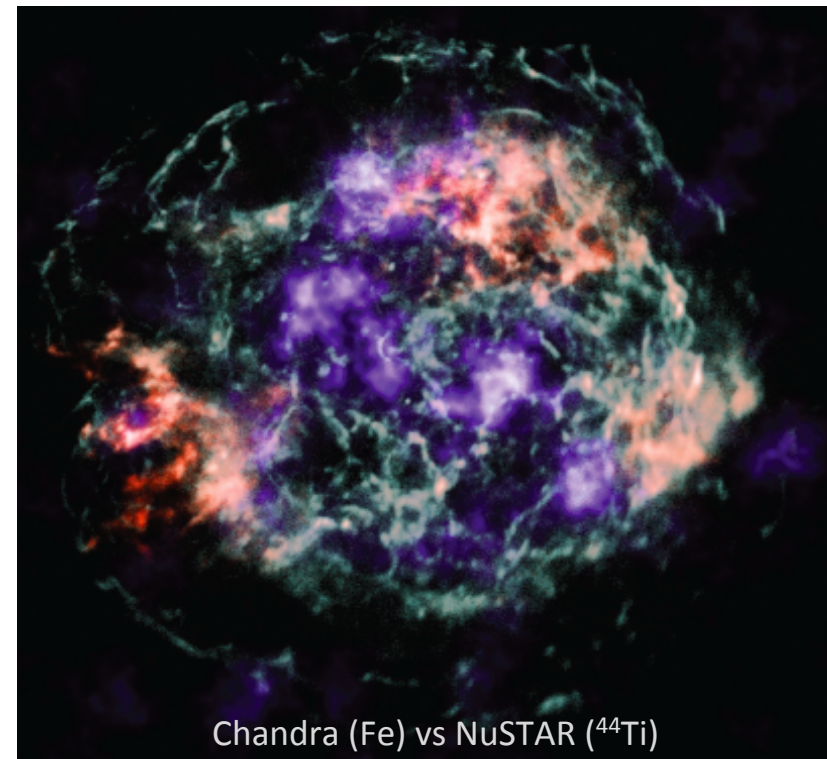
^{44}Ti Ejected Mass $\sim 0.8\text{-}2.5 \cdot 10^{-4} M_{\odot}$

★ Imaging in hard X-rays (3-79 keV)

→ ^{44}Ti lines at 68,78 keV

☞ Cas A: first mapping of radioactivity in a SNR ever

- Both ^{44}Ti lines detected clearly
- line redshift 0.5 keV
→ 2000 km/s redshift asymmetry
- Image differs from Fe!!
- ^{44}Ti flux:
consistent with earlier measurements
- continuum: harder near rim



Chandra (Fe) vs NuSTAR (^{44}Ti)

☞ SN1987A: 6 σ , consistent with INTEGRAL flux (no image)

^{44}Ti g-rays from Cas A

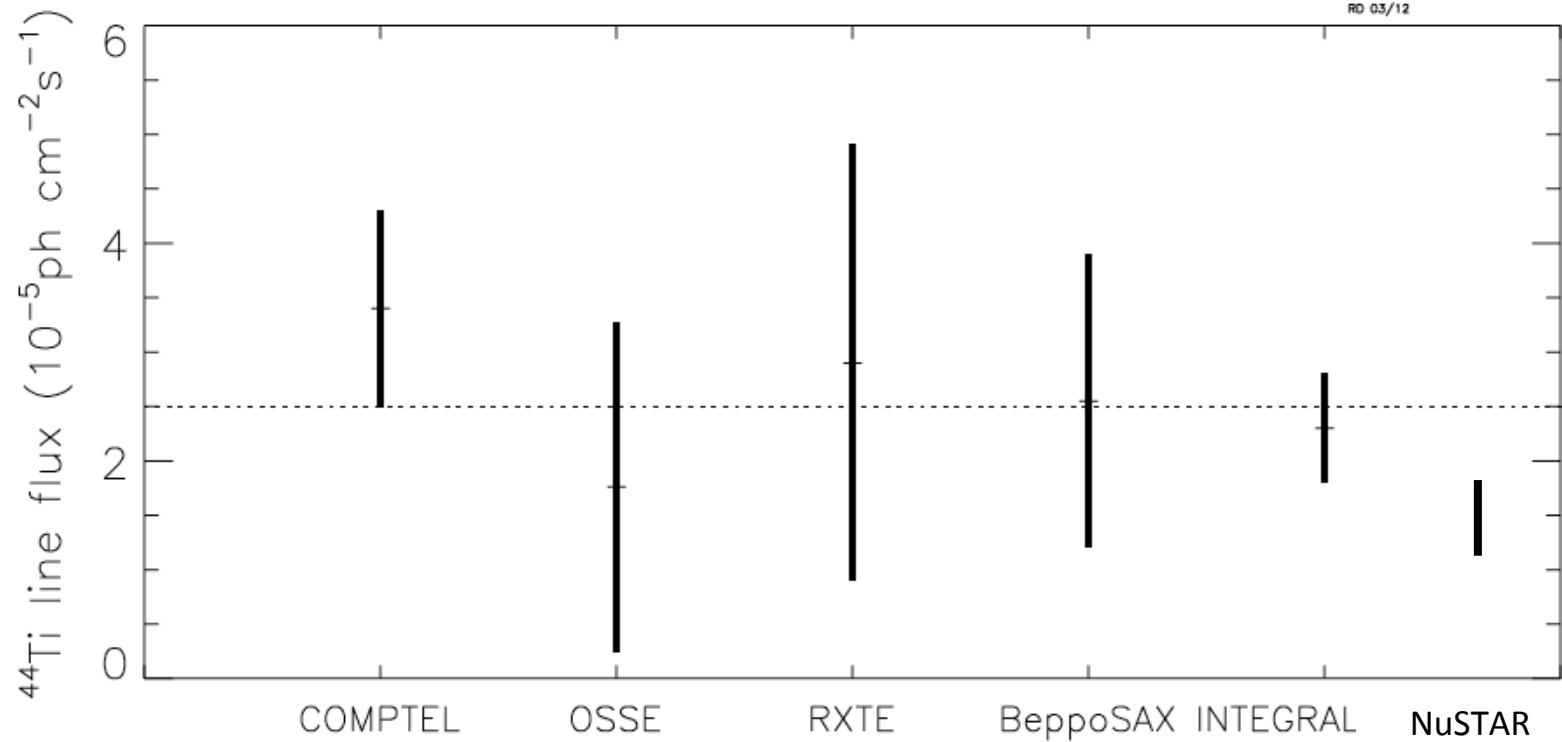


$t=85\text{y}$ (Ahmad et al. 2006)

89 y $^{44}\text{Ti} \rightarrow ^{44}\text{Sc}^* \rightarrow ^{44}\text{Ca}^* + e^+$ 78, 68; 1157

$t_{1/2}=85\text{y}$, EC

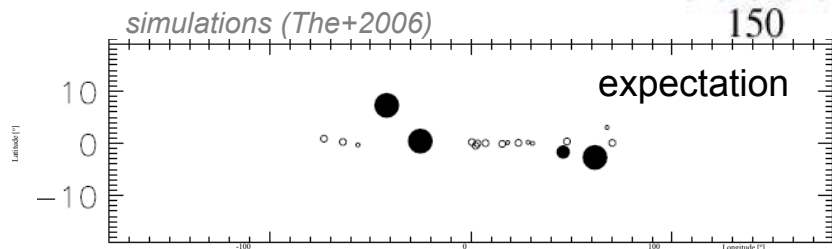
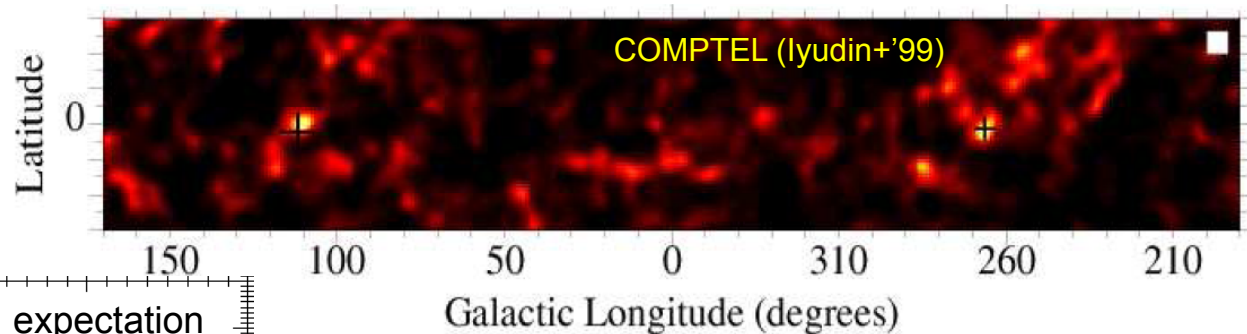
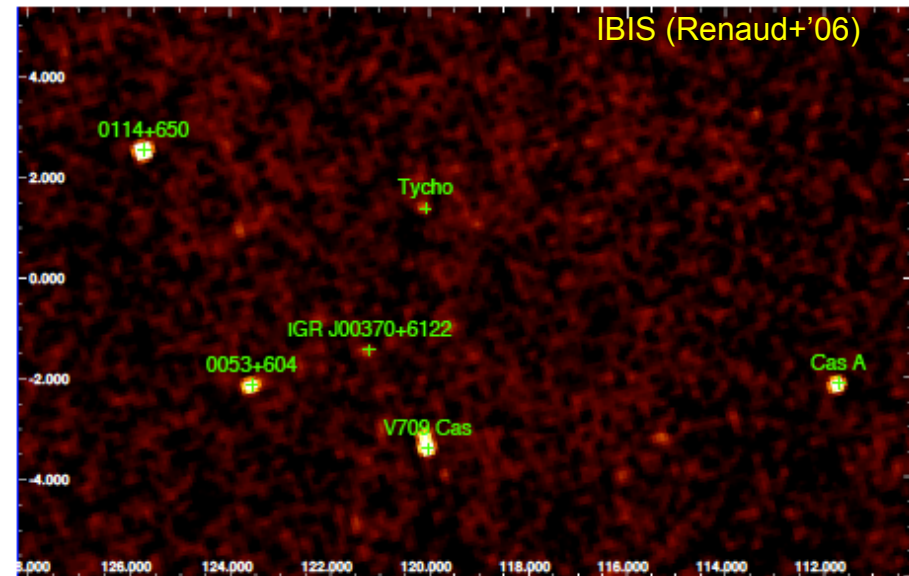
^{44}Ti



^{44}Ti Ejected Mass $\sim 1.23 \pm 0.25 \cdot 10^{-4} M_{\odot}$

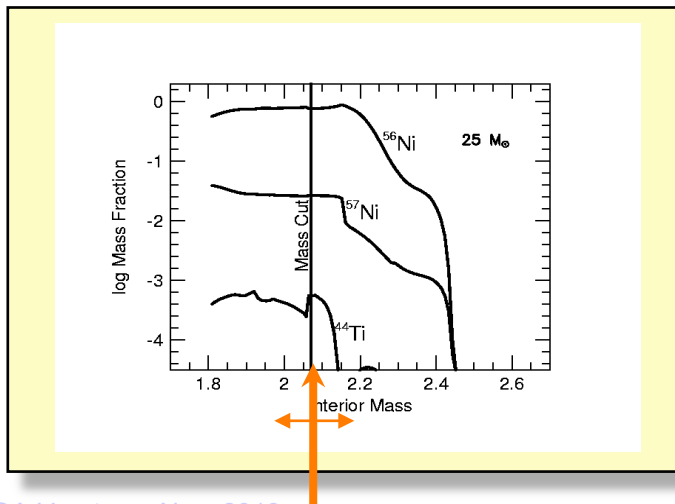
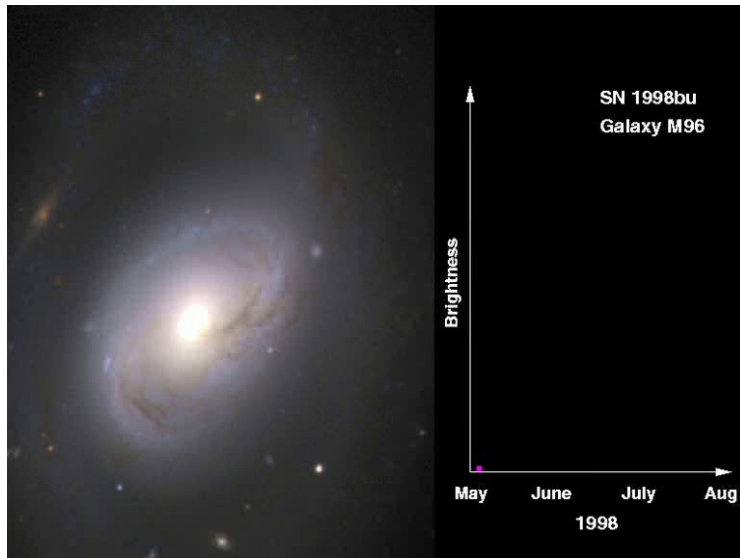
Are Core Collapse Supernovae ^{44}Ti Sources?

- ★ Sky Regions with Most Massive Stars are ^{44}Ti Source-Free (expect ~a few!)
- ★ Cas A is the ONLY Source Seen in our Galaxy



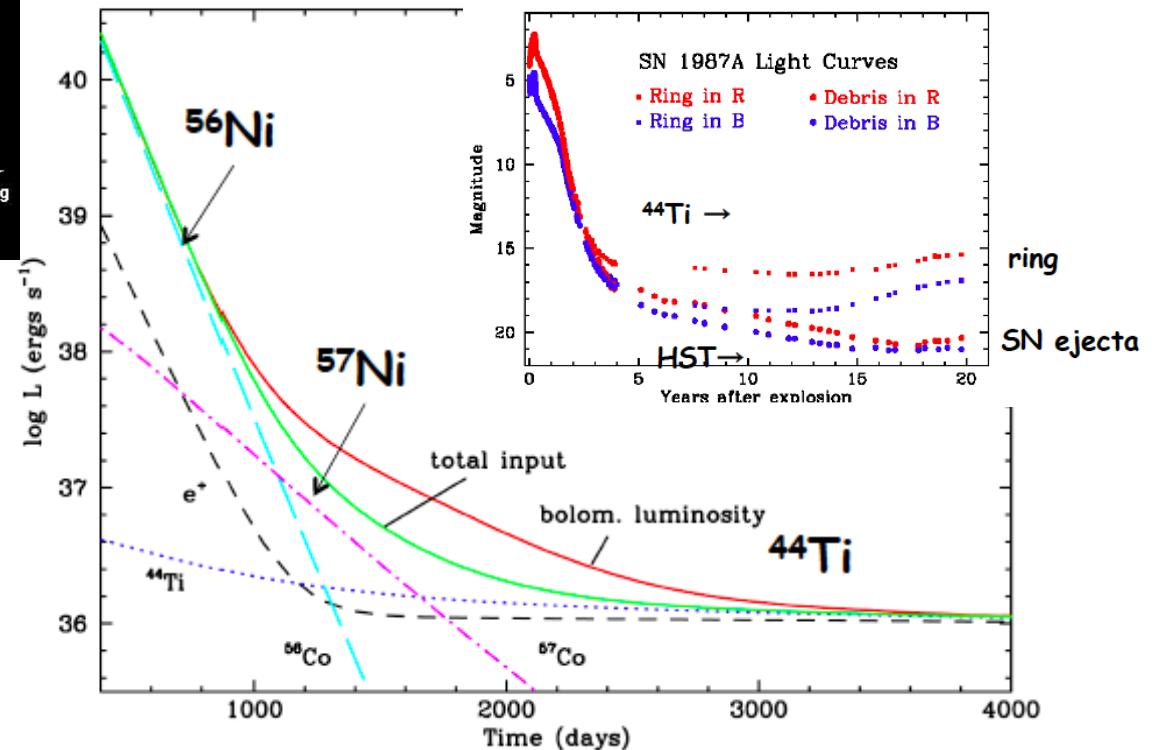
Observing Supernova Radioactivity: SN1987A

- Radioactivity as Sustained Energy Source!



SN 1987A radioactivities

CF & Kozma 1993,



SN1987A with INTEGRAL

- INTEGRAL Line Band Imaging with IBIS (*Grebenev+2012*)
 ➞ Detection at 5 σ significance (6 Ms exposure)

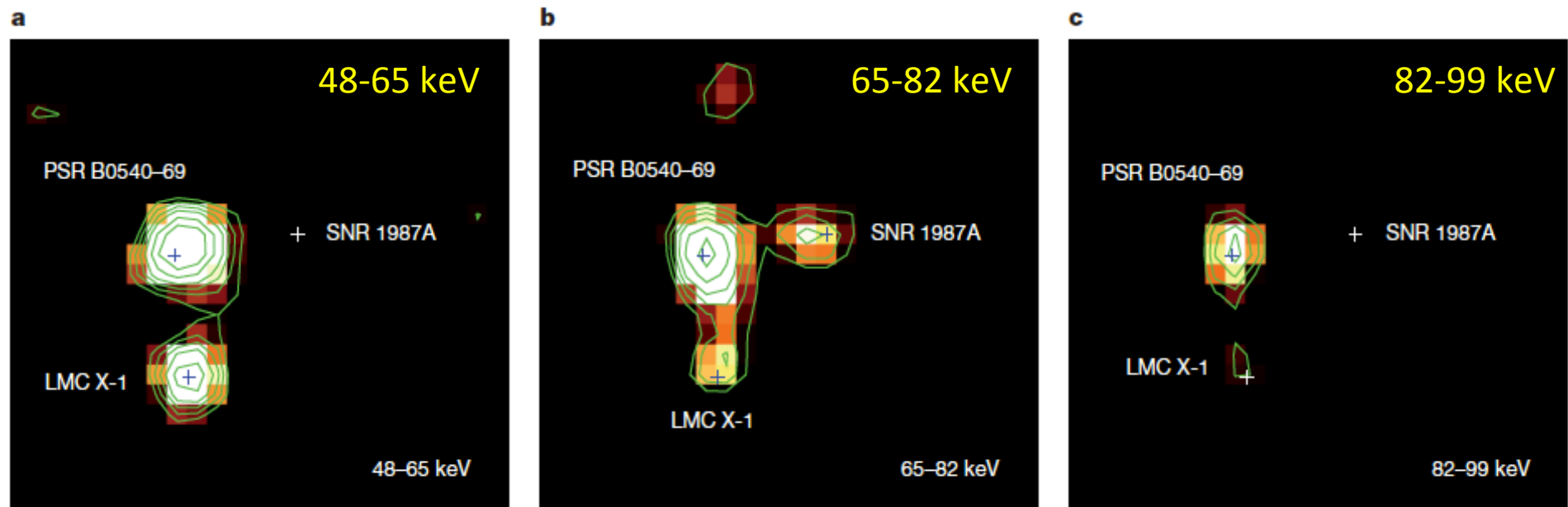


Figure 1 | Hard-X-ray images indicating the detection of ⁴⁴Ti emission lines from SNR 1987A. a–c, Maps of the signal-to-noise ratio (S/N) of the 1.5° × 1.5° sky region around SNR 1987A accumulated in three energy bands with the IBIS/ISGRI telescope on board INTEGRAL during observations in 2003–2011 (~6.0 Ms of real exposure or ~4.2 Ms of dead-time-corrected exposure): 48–65 keV (a); 65–82 keV (b); 82–99 keV (c). The maps were

reconstructed using standard techniques²⁷ with contours given at S/N levels of 2.7, 3.3, 3.9, 4.5, 5.4 and 6.3. Two well-known sources, PSR B0540–69 and LMC X-1, are seen bright in all three images, but SNR 1987A is confidently detected only in b, in the band that contains the 67.9- and 78.4-keV direct-escape lines of radioactive ⁴⁴Ti decaying inside the ejecta.

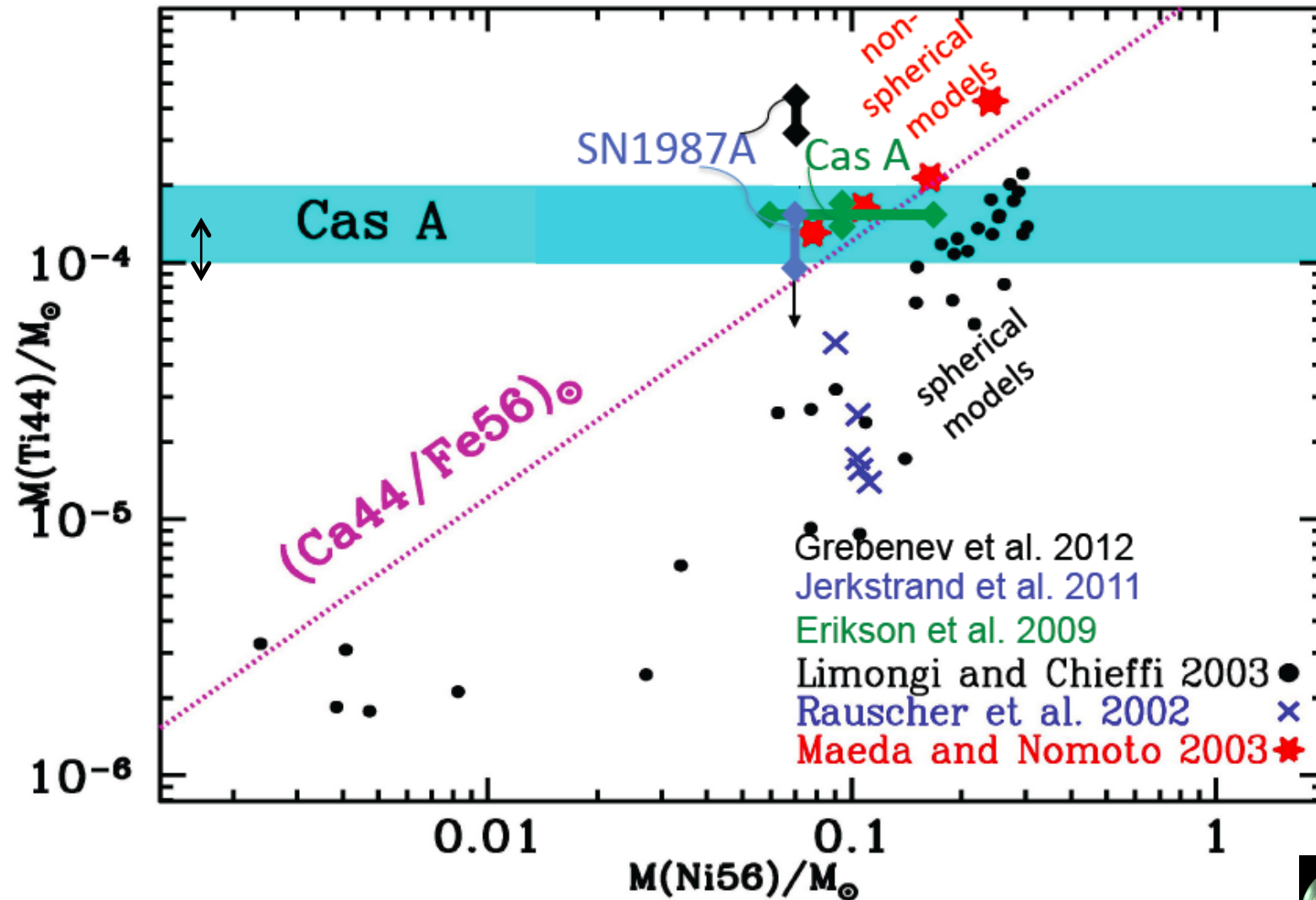


⁴⁴Ti Ejected Mass $\sim 3.1 \pm 0.8 \cdot 10^{-4} M_{\odot}$



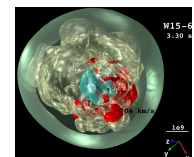
LC Analysis Jerkstrand+2011: $\sim 1...2 \cdot 10^{-4} M_{\odot}$

“Abnormal” Core Collapse Supernovae as ^{44}Ca ($=^{44}\text{Ti}$) Sources?

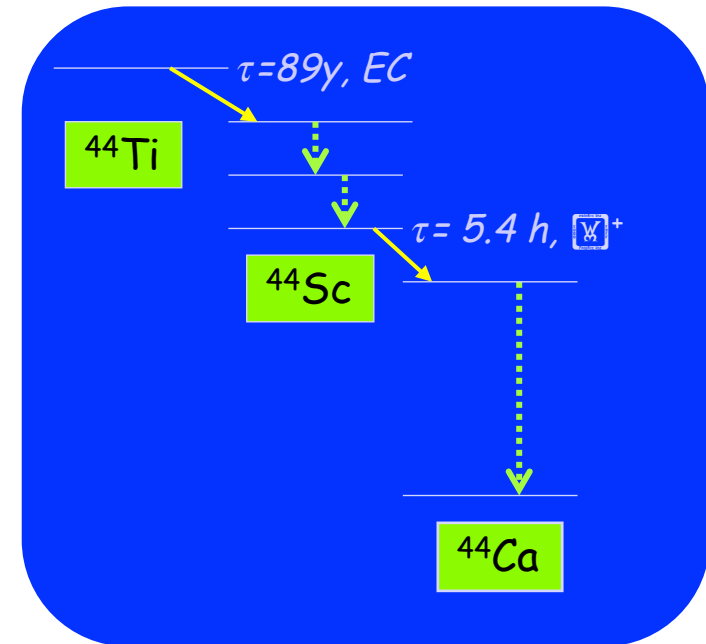
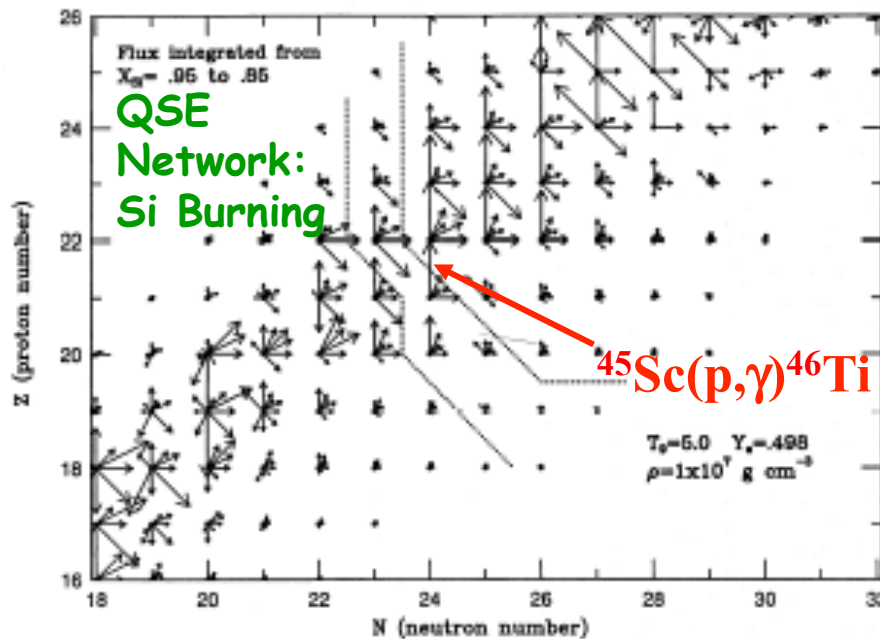


⇒ Only Non-Spherical Models Seem to Reproduce Observed $^{56}\text{Ni}/^{44}\text{Ti}$ Ratios

⇒ The et al. 2006



- Why are ^{44}Ti Gamma-Rays Interesting?



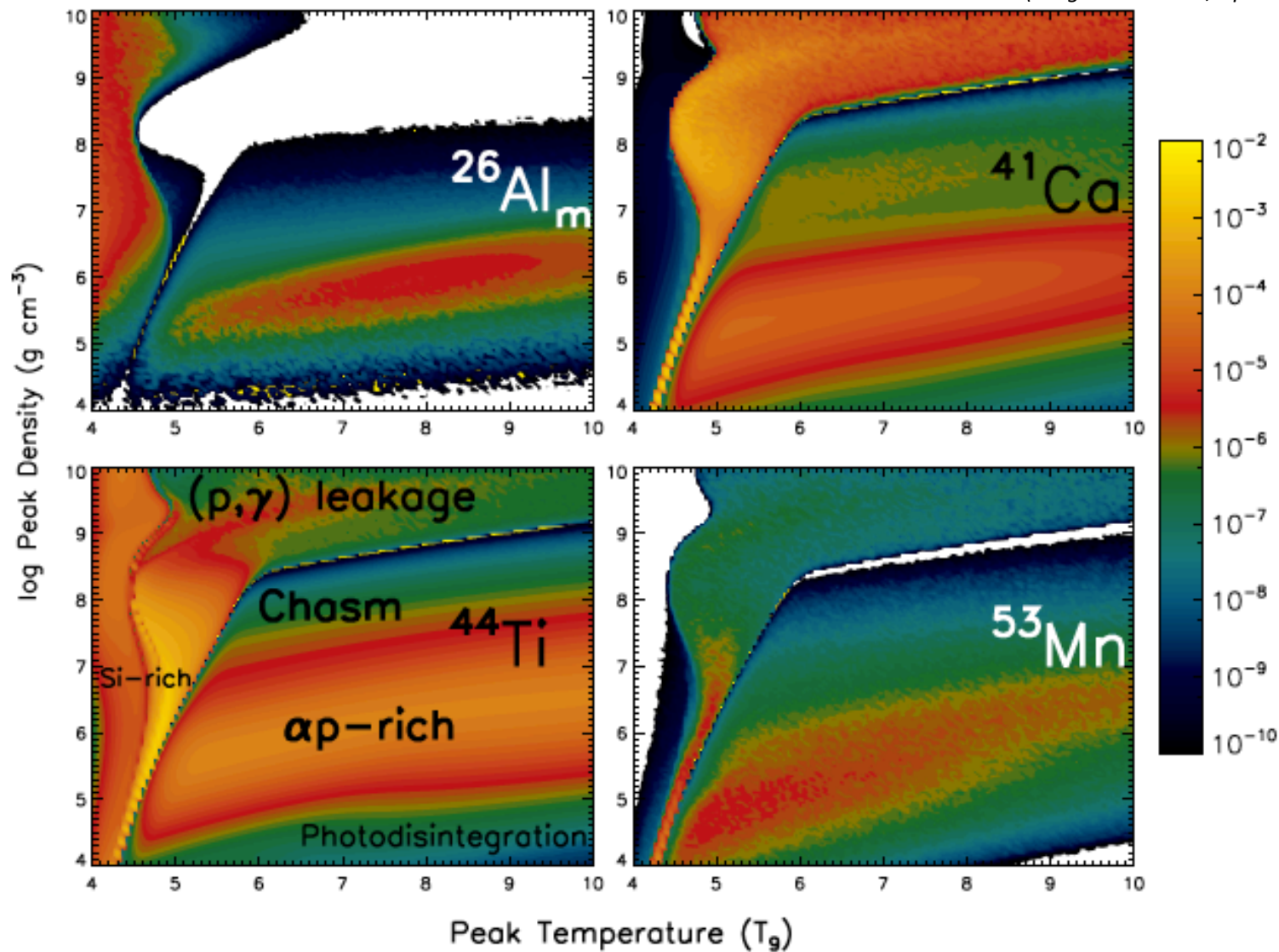
★ Complex Nuclear-Reaction Dynamics

👉 A Specific Isotopic Abundance as “Calibration Point”

^{44}Ti Synthesis in cc-SNe



NuGrid collaboration (Magkotsios et al., ApJ 2011)



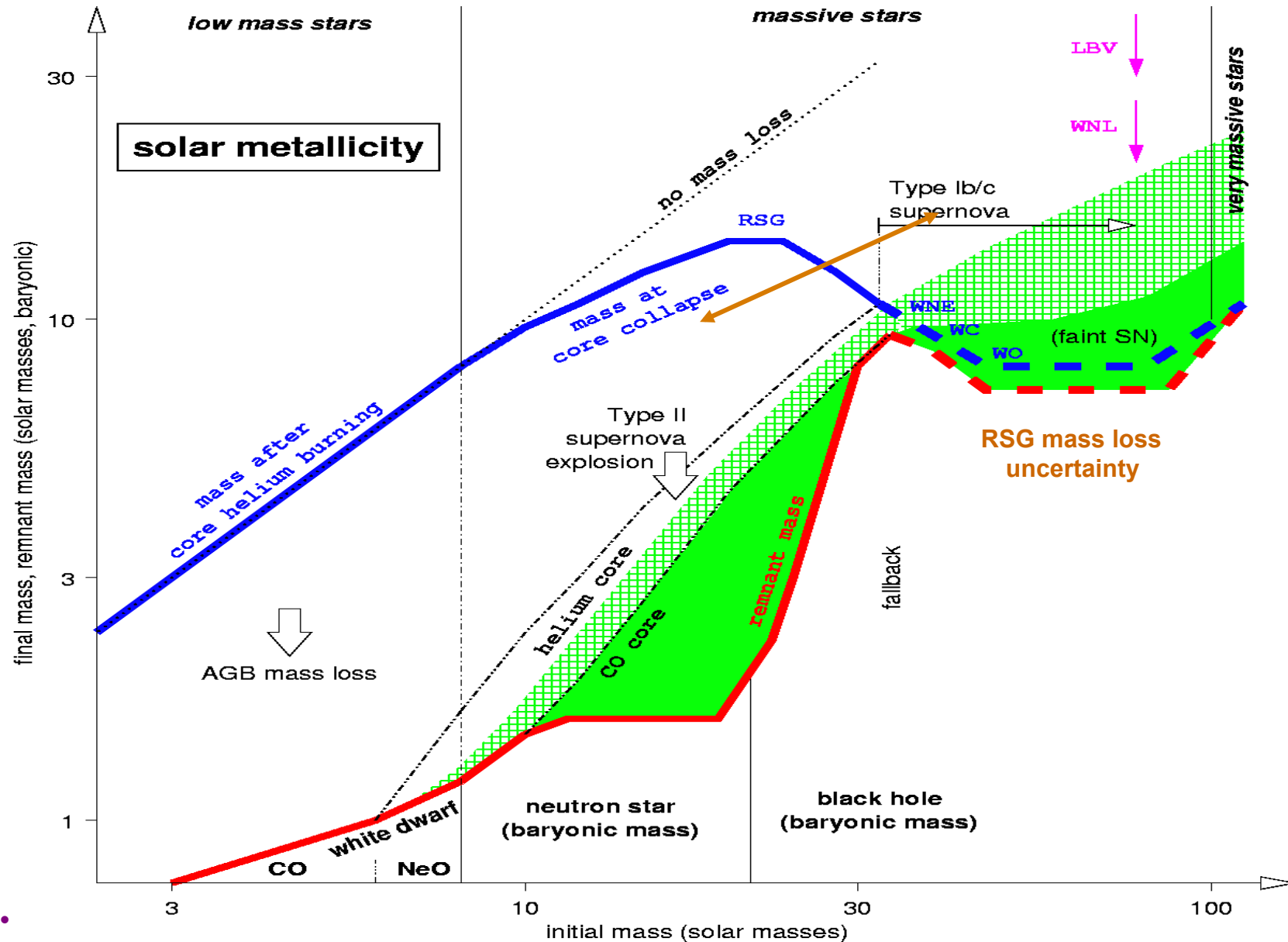
“For each region only certain reactions affect the yields of ^{44}Ti ”

Sources of Supernova Explosion Asymmetries



- **Neutrino-Driven Convection**
 - 👉 Large-scale "Boiling" of Neutrino-heated Matter above Neutrinosphere
- **Advection-Acoustic Instabilities**
 - 👉 Triggering of large-scale waves from inflowing/accreting material
- **Richtmeyer-Meshkov Instabilities**
 - 👉 Inclined shock wave interaction with H/He interface
- **Rotation and Magnetic-Field Interaction**
 - 👉 Differential Rotation from Collapsing Core -> Toroidal Magnetic Field
- **Rotational Fragmentation of PNS, NS Explosion**
 - 👉 Rotational Break-Up of PNS into NS Binary
 - 👉 NS Explosion at Minimum-Stable Mass Limit

cc-SN Types: Impact of pre-SN mass loss



Unusual/unexpected Supernovae



- other Types of cc-SN-like Events??

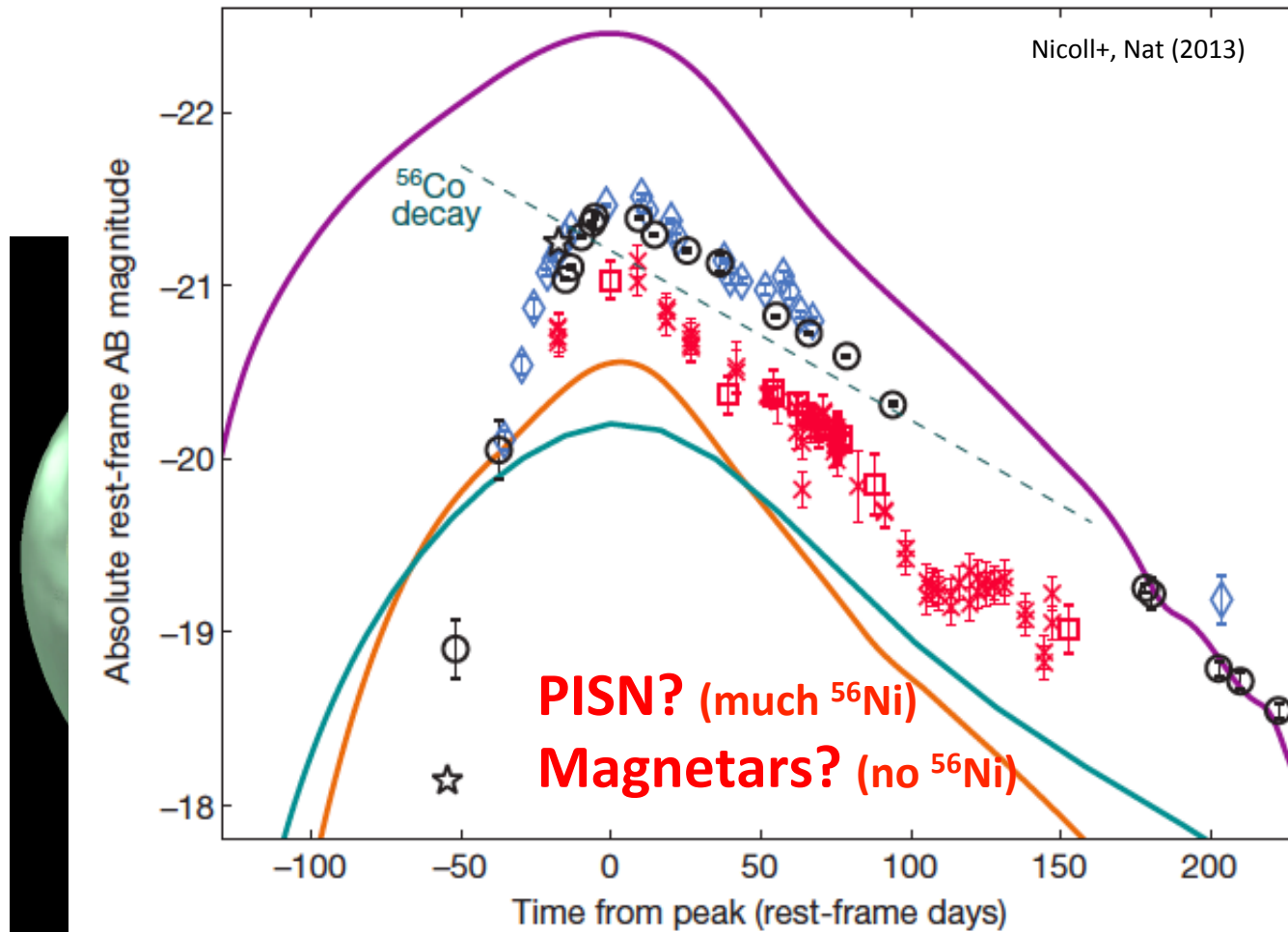


Figure 1 | Optical light curves of slow-fading super-luminous supernovae.

Collapsars



- Model:

- ➡ Massive Star Core Collapse to Black Hole
- ➡ Accretion Disk Formation -> Preferred Jet Axis -> GRB

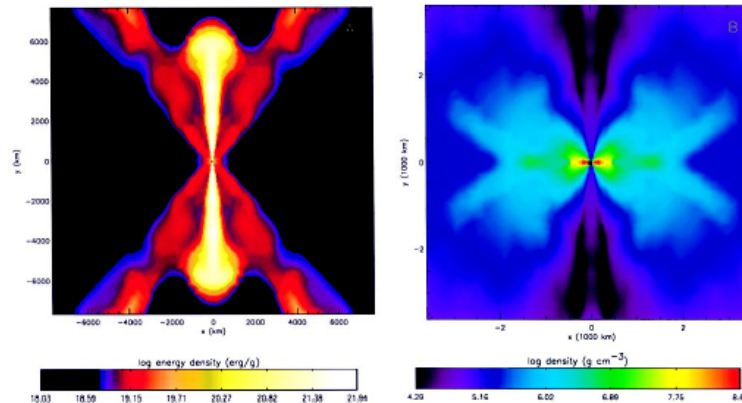
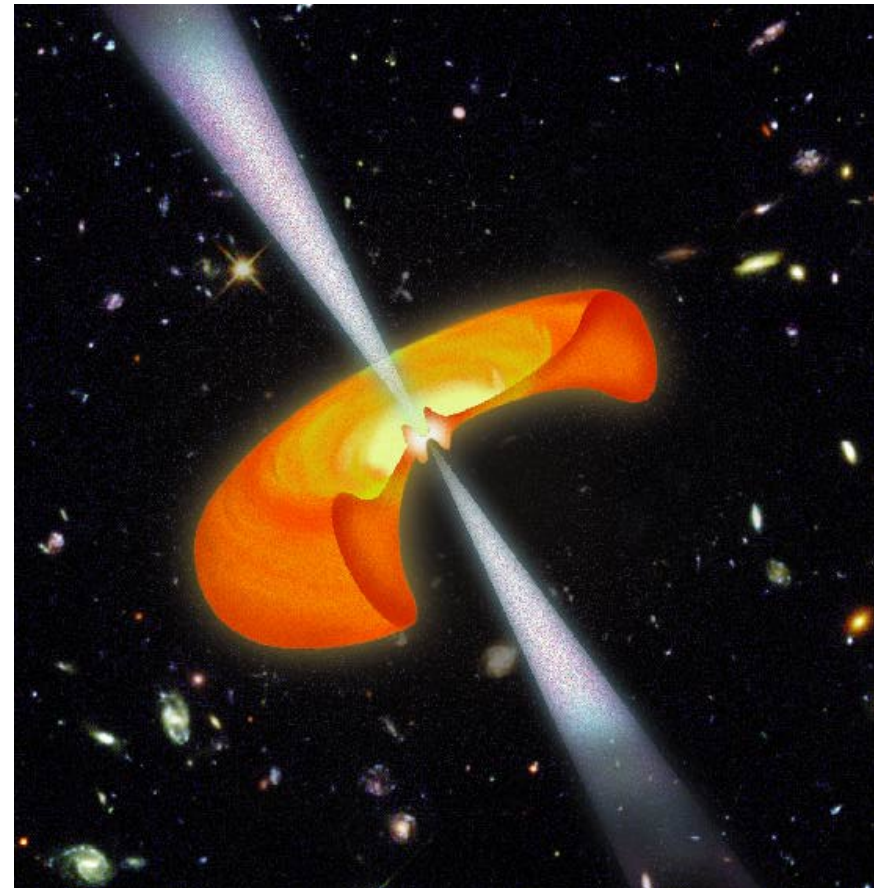


FIG. 3. Two-dimensional hydrodynamic simulations (18) show the formation of a low-density region above the poles of a rotating black hole formed in the collapsar model. (A) The energy density in the jets and surrounding area ~ 1 sec after its initiation. The jet has moved to a distance of $\sim 10,000$ km, and its opening angle is of order 10 degrees. (B) The density contours ~ 16 sec after the onset of collapse. The yellow/red region shows the dense accretion disk around the black hole.

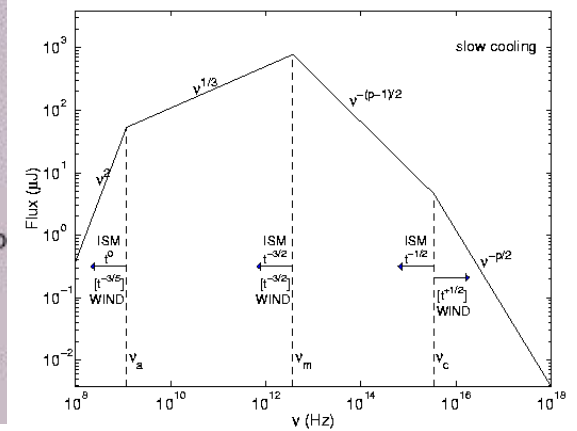
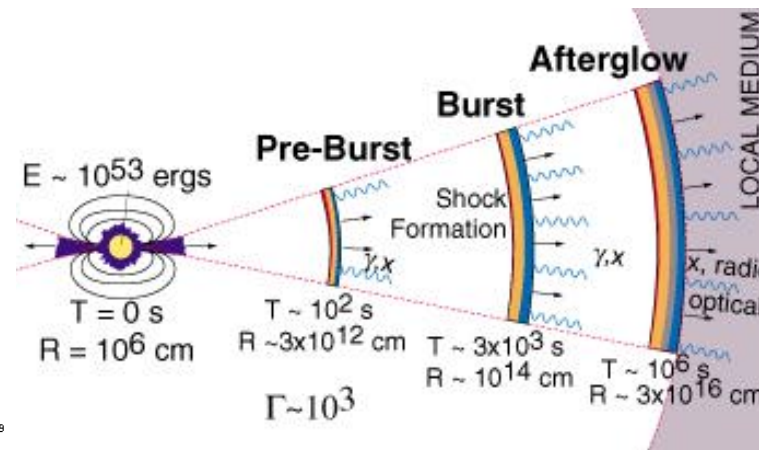
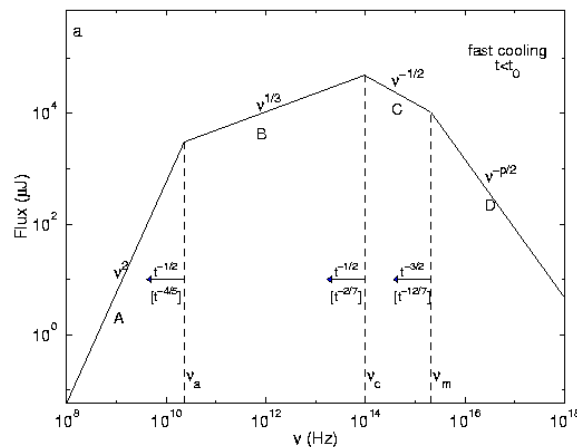
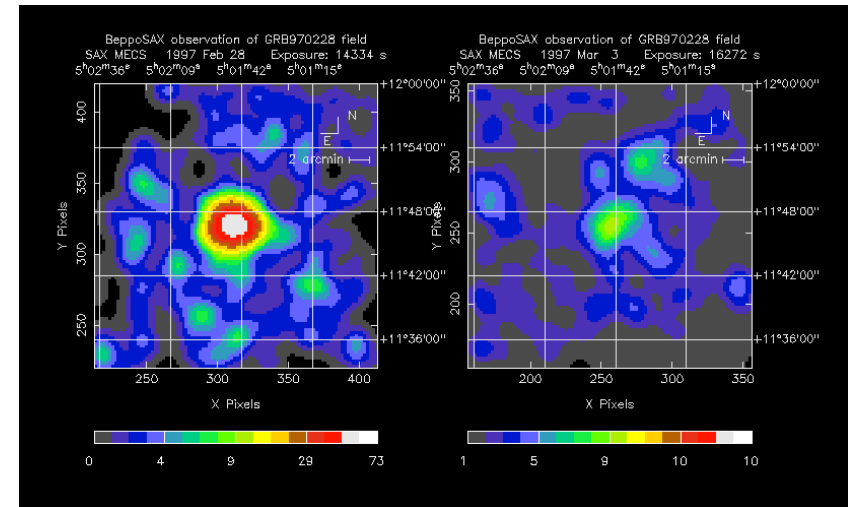
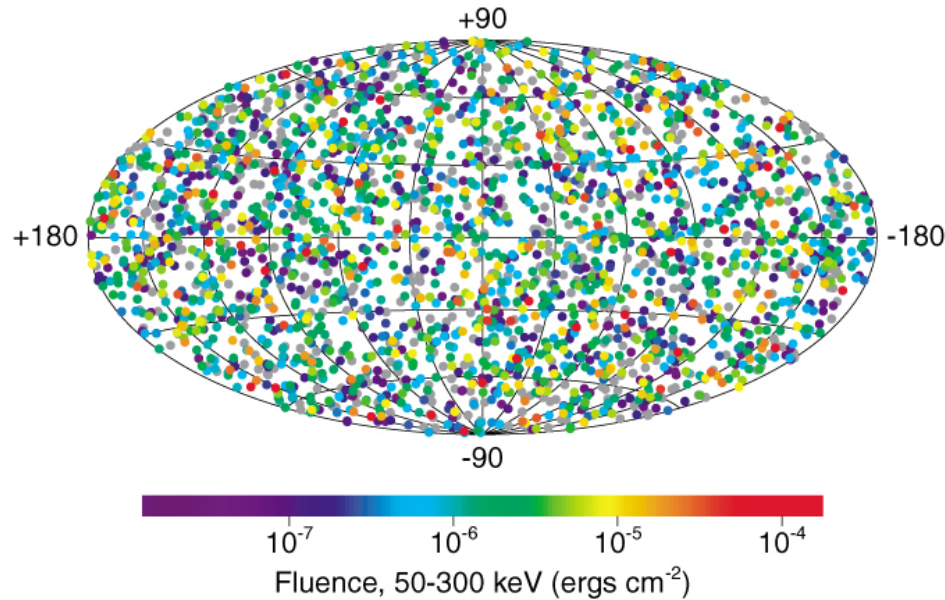


Gamma-Ray Bursts

prompt emission

afterglow emission

2704 BATSE Gamma-Ray Bursts



The Star Formation History in the Universe

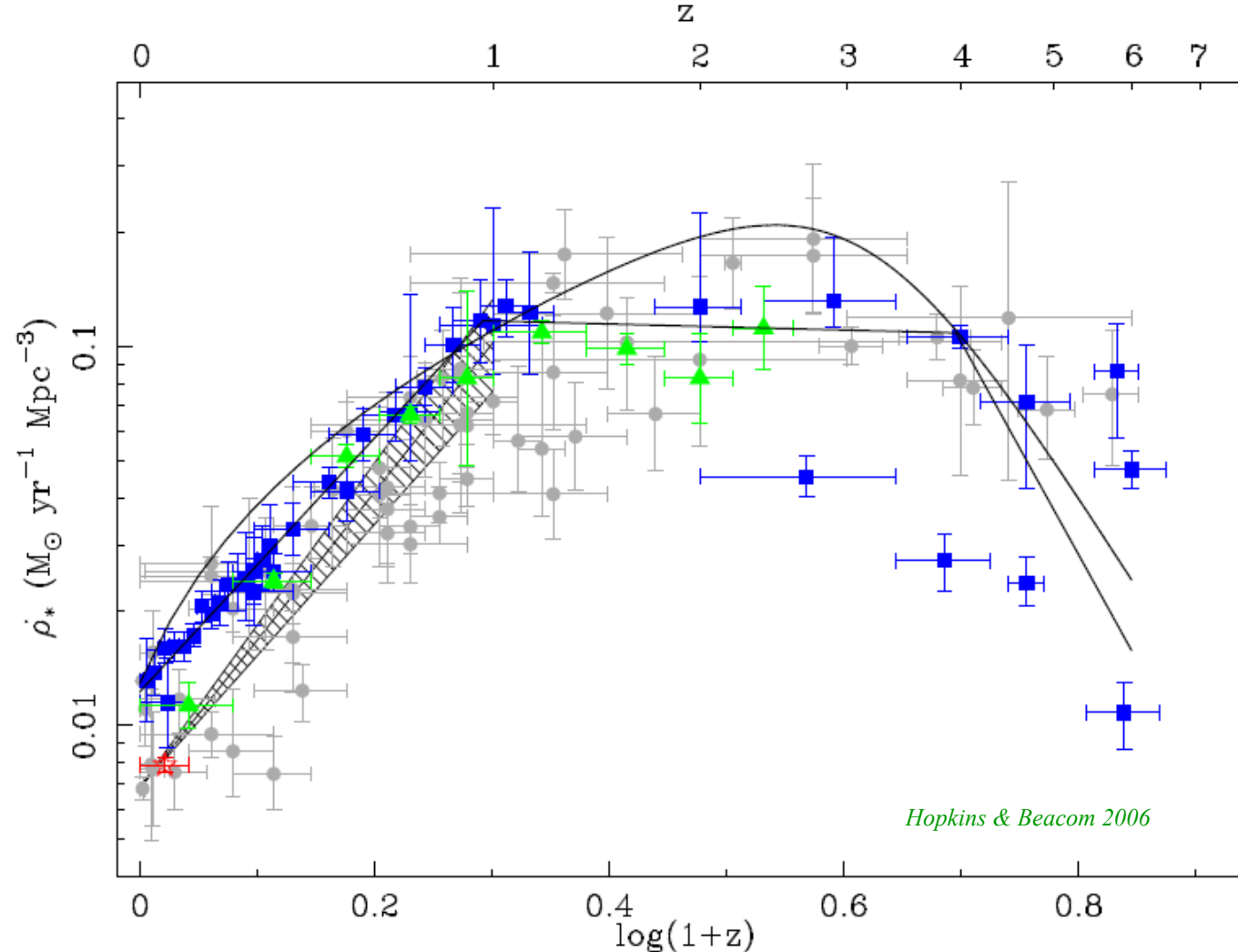
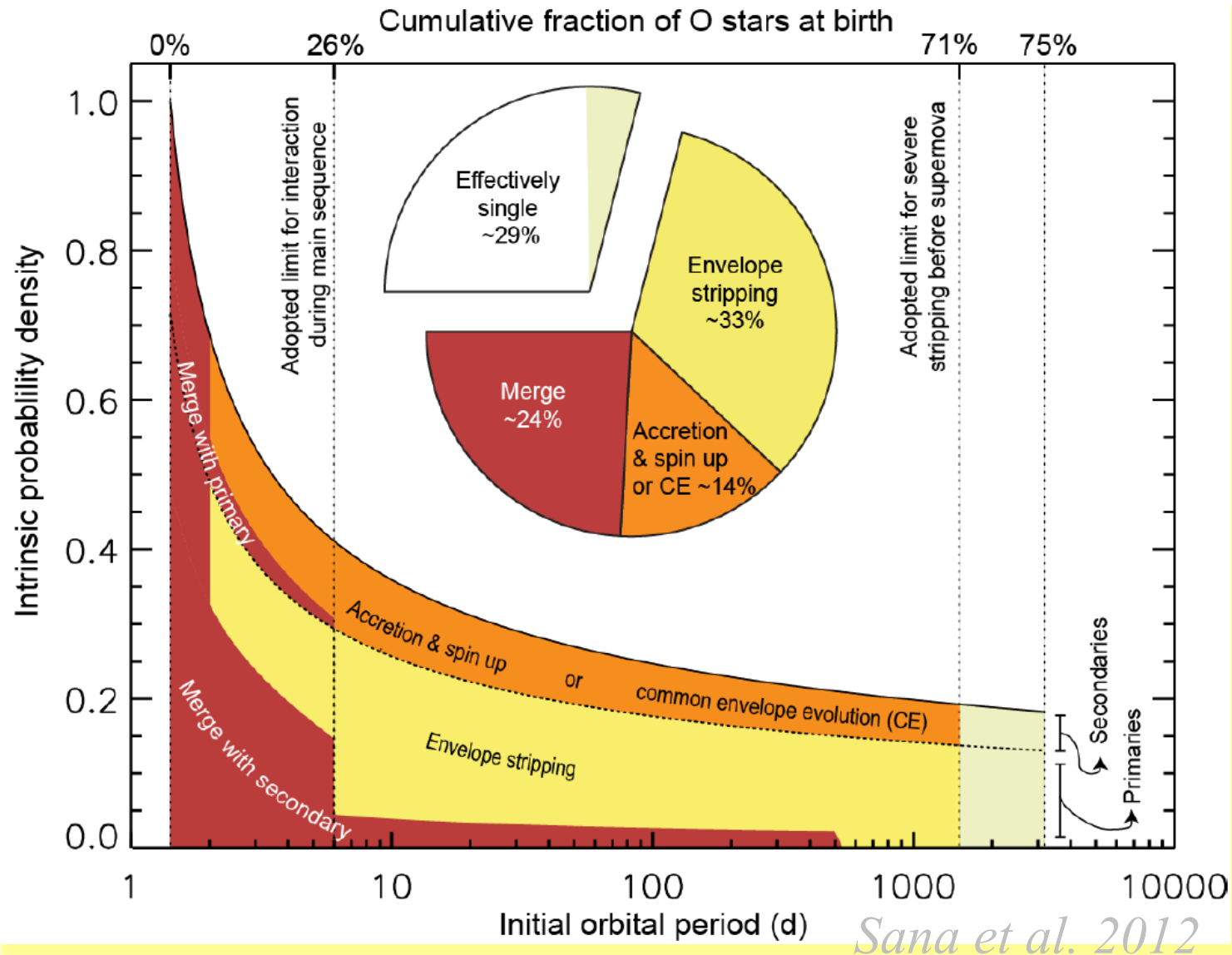


FIG. 1.— Evolution of SFR density with redshift. The grey points are from the compilation of Hopkins (2004). The hatched region is the FIR ($24\mu\text{m}$) SFH from Le Floch et al. (2005). The green triangles are FIR ($24\mu\text{m}$) data from Pérez-González et al. (2005). The open red star at $z = 0$ is based on radio (1.4 GHz) data from Mauch (2005). Blue squares are UV data from Baldry et al. (2005); Wolf et al. (2003); Arnouts et al. (2005); Bouwens et al. (2003b,a); Bunker et al. (2004); Bouwens et al. (2005a); Ouchi et al. (2004). The solid lines are the best-fitting parametric forms (see text for details of which data are used in the fitting). Data shown here assume the SalB IMF. Although the FIR SFH of Le Floch et al. (2005) is not used directly in the fitting, it has been used to effectively obscuration-correct the UV data to the values shown, which are used in the fitting. Note that the top logarithmic scale is labelled with redshift values, not $(1+z)$.

Stellar Evolution: Beyond Single Stars

- Binary System → Different Evolution



The Role of Binaries



★ **Mass Flow from Companion Star is the Key Agent**

★ **Depending on the Type of Star, Dominating Effect is**

☞ **Modified Stellar-Evolution Phases**

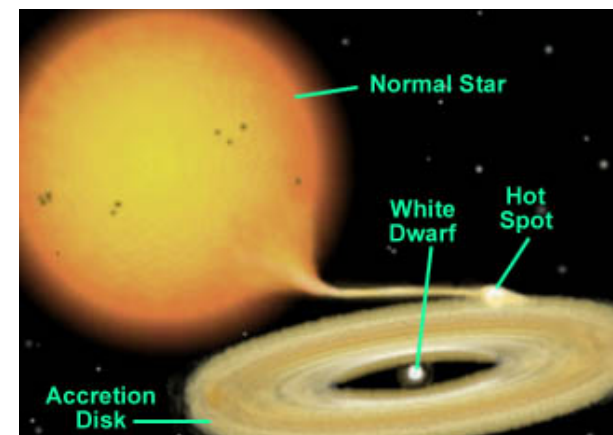
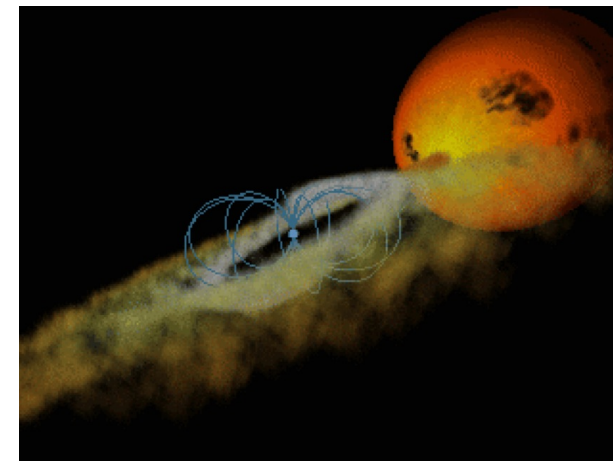
- for stars where interiors are "sensitive" to surface effects

☞ **Special Observables Related to Mass Accretion**

- for stars where mass flow incurs substantial heating/energy release

☞ **Special Processes Related to Additional Mass on Stellar Surface**

- for stars where critical conditions can be reached through added mass



Nuclear Burning in Binaries

Nova

Supersoft sources

Supernova Ia

X-ray bursts

transient H burning on WD

stable H burning on WD

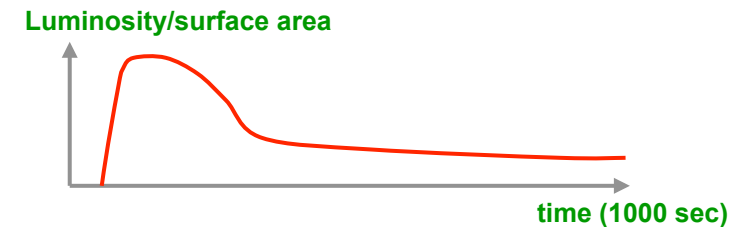
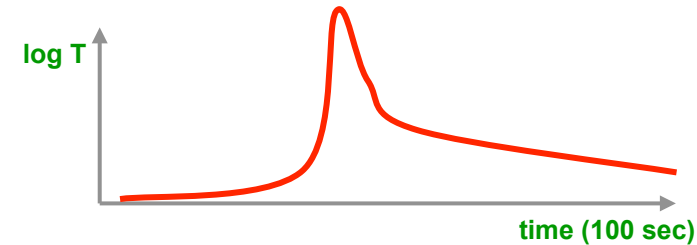
explosive C burning in WD

transient He burning on NS

Dynamical Characteristics of a Classical Nova



- “Smoldering” for $>10^3$ years, until Runaway
- Temperature Peak after ~ 200 sec
- T_{peak} in deepest H-rich zone 2 to 3 10^8K
- Surface Luminosity peaks after ~ 2000 sec then slow decay over months; it takes \sim days to reach visual maximum due to expansion (initial steep rise occurs when temperature is maximum)
- At visual peak the photosphere starts to retreat, and reveals inner & hotter regions, i.e. surface temperature rises from 10^4 to 10^6K (UV-brightening): $T_{\text{photosphere}} = 15280 \cdot 10^{\text{Dm}_v/7.5} \text{ K}$ after visual decline by Dm mag's
- “fast” novae = $\text{dm}_v/\text{dt} \sim 0.1 \text{ mag/day}$
- “slow” noave = $\text{dm}_v/\text{dt} \sim 0.01 \text{ mag/day}$
- Bolometric luminosity \sim flat for months
- Dust formation after 50-100 days, \rightarrow visual brightness fading, bright in IR at $T \sim 700\text{K}$



Relevant time scales:

$$\tau_{\text{accretion}} \sim \frac{M_{\text{acc}}}{\dot{M}} \quad \sim 10^4 \dots 10^5 \text{ y}$$

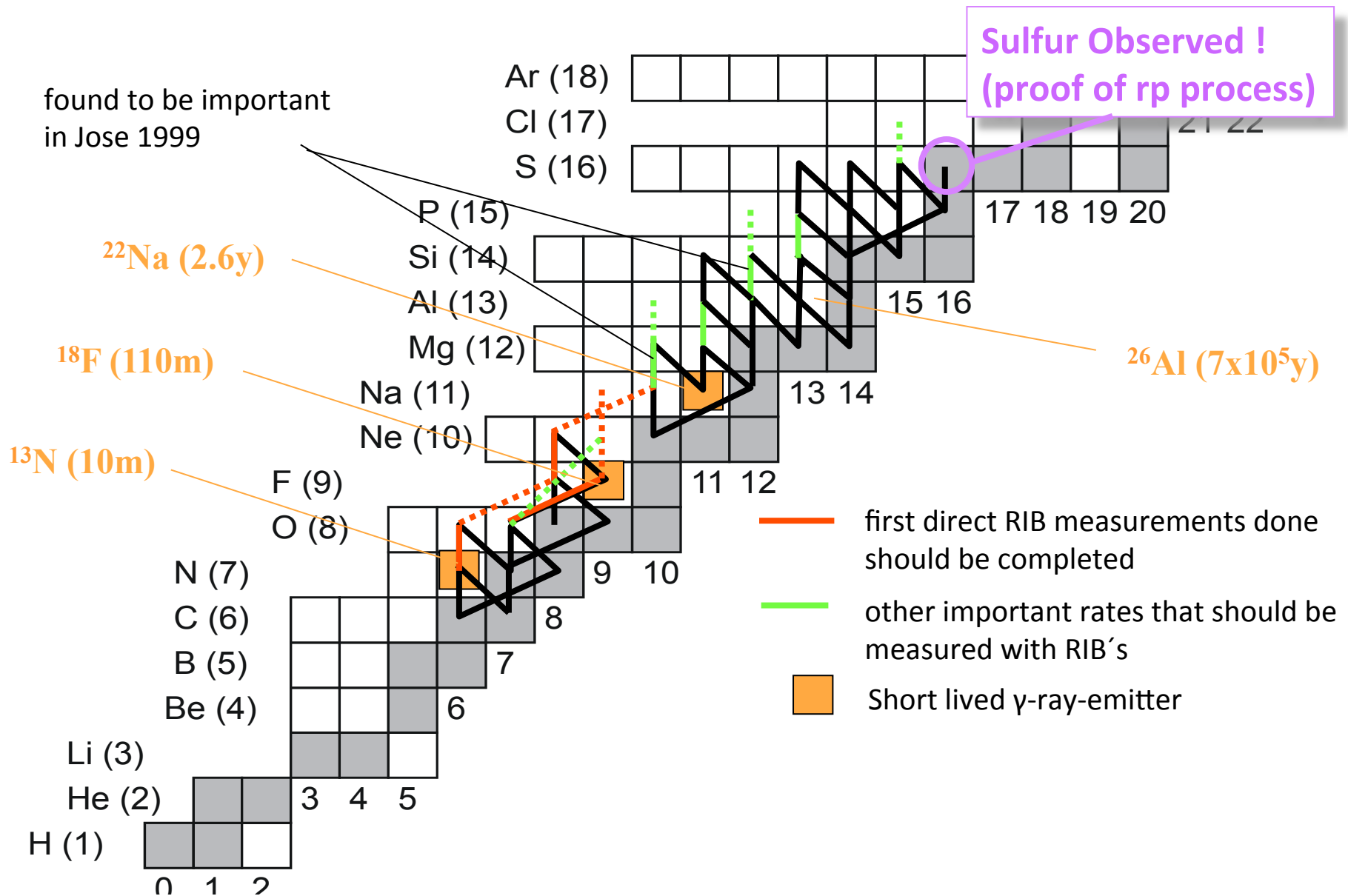
$$\tau_{\text{nuclear}} \sim \frac{C_p T}{E_{\text{nuclear}}} \quad \sim \text{sec}$$

$$\tau_{\text{hydrodyn}} \sim \frac{h_{\text{pressure}}}{c_{\text{sound}}} \quad \sim \text{hrs} \dots \text{days}$$

Nuclear-reaction sequence in novae

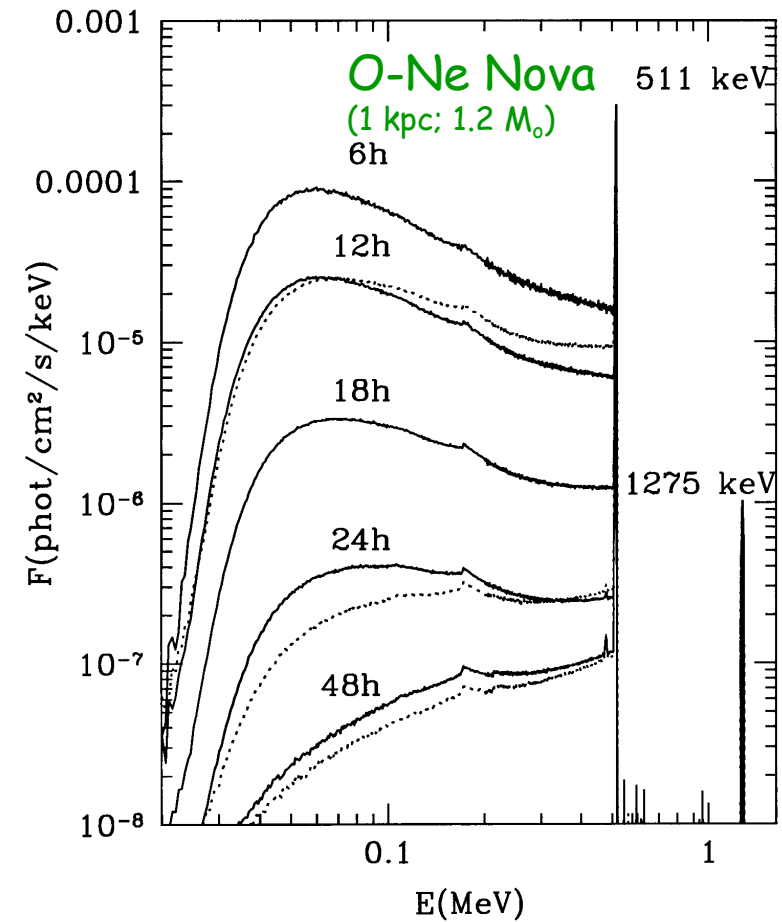
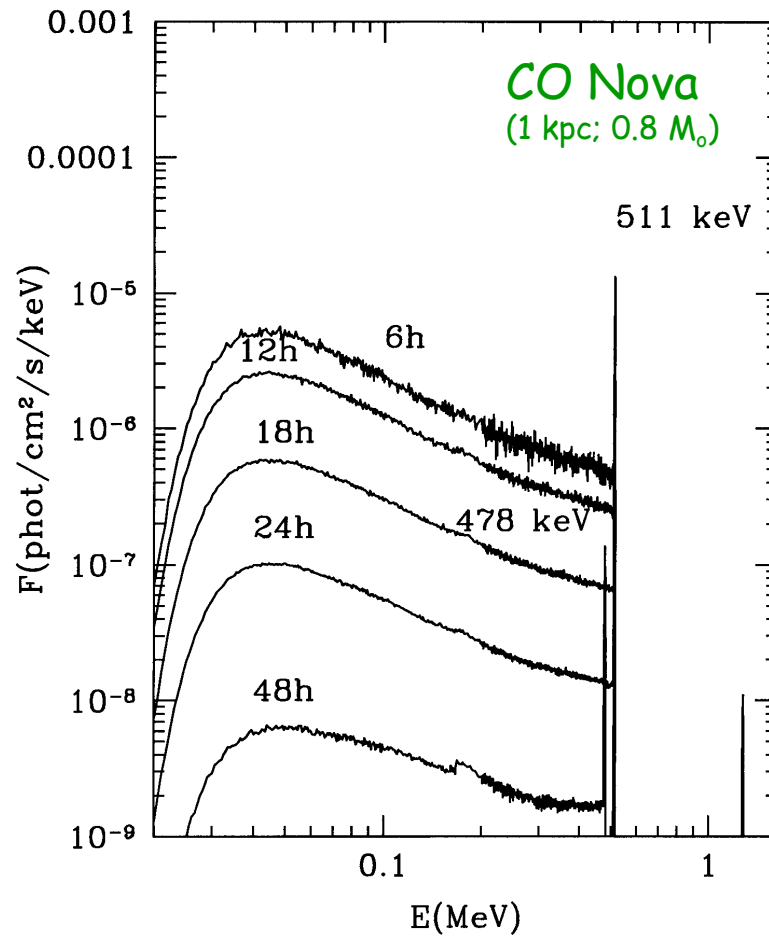


Example: ONeMg Nova, 1.35 M_{\odot} white dwarf (Starrfield 1996) $t \sim 3\text{min}$, $T_{\text{max}} = 0.36\text{GK}$



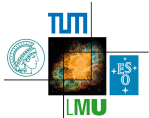
Nova Diagnostic Prospects: Nuclear Lines

e.g. Jose & Hernanz 1998; 2007



- ★ **Brief Annihilation Flash**
- ★ **β Decay Continuum**
- ★ **^{22}Na Radioactivity (O-Ne Novae)**

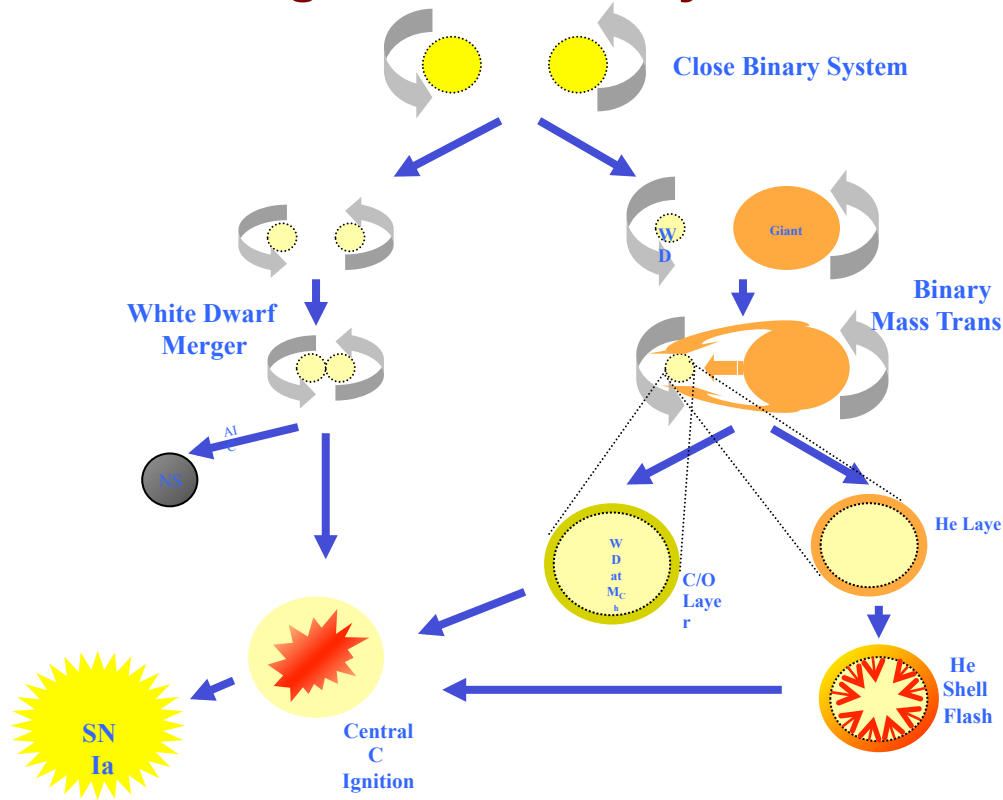
(before optical nova!)



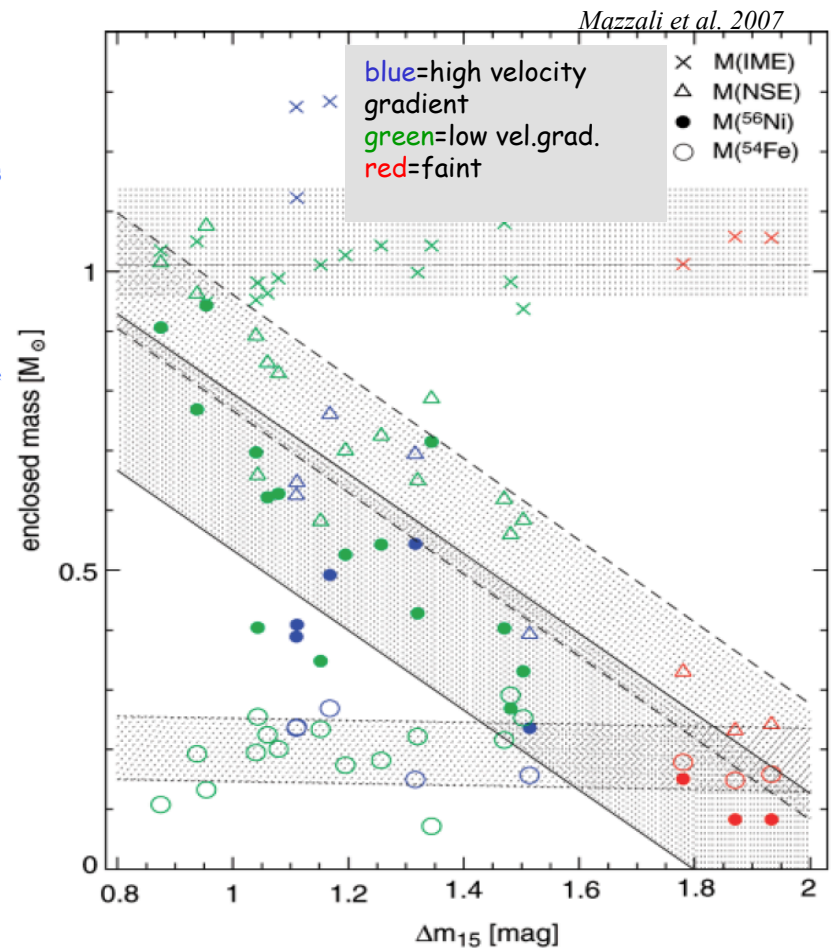
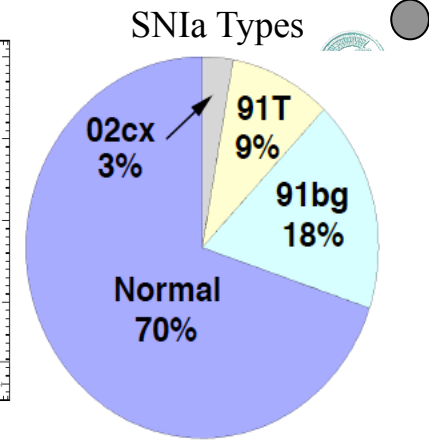
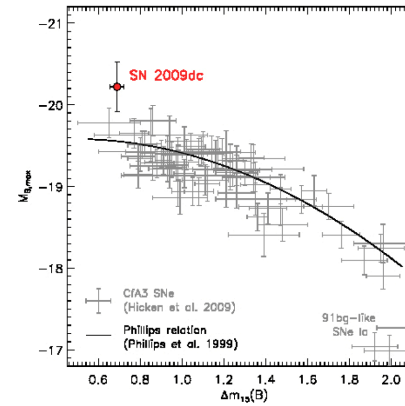
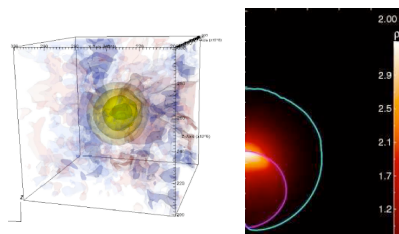
SN Ia Diversity

SN Ia

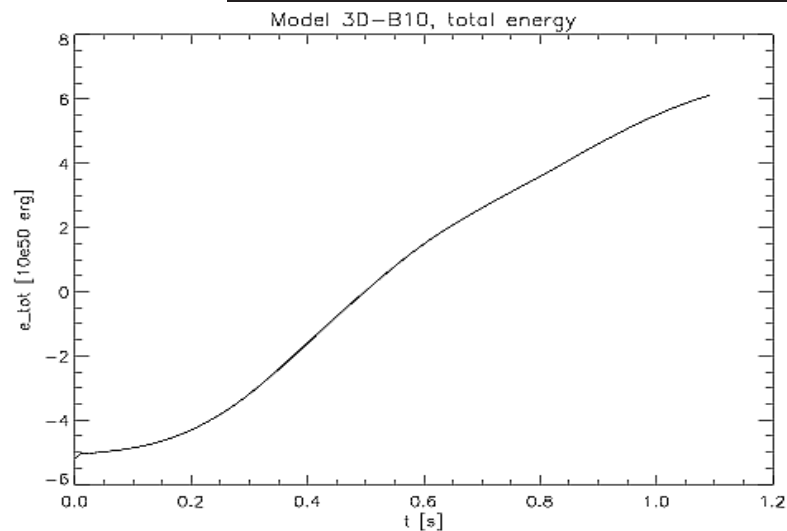
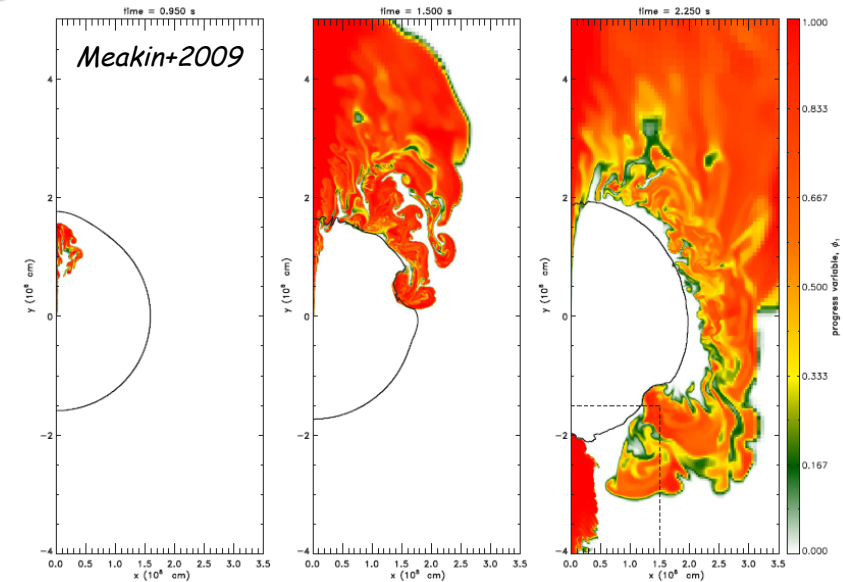
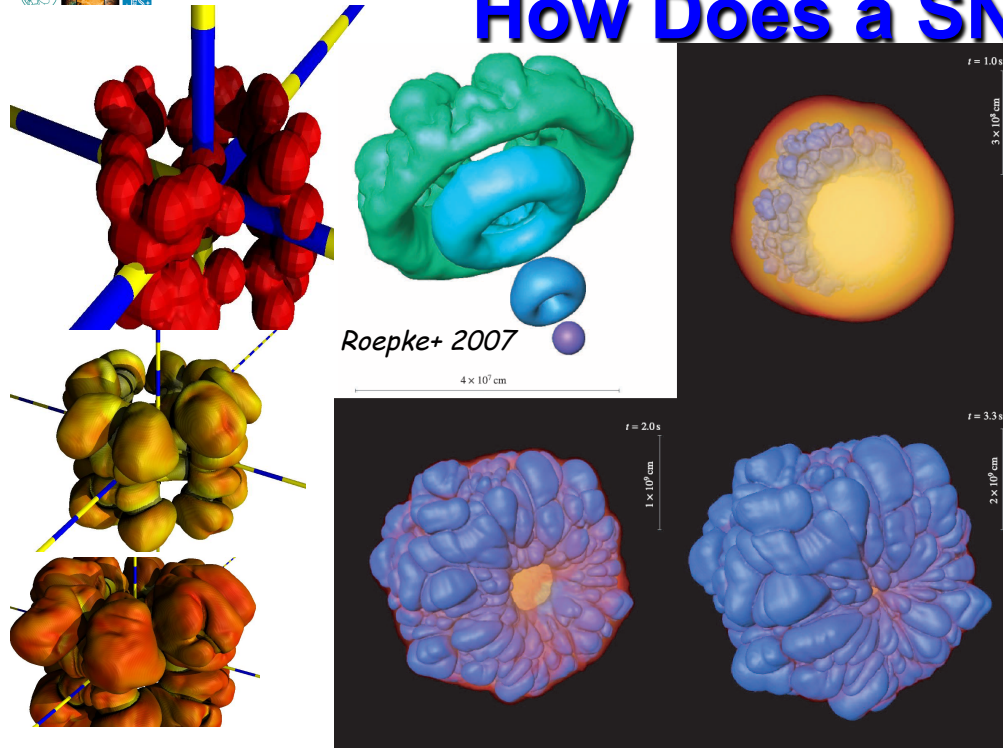
Progenitor Diversity?



Ignition Physics?



How Does a SNIa Explode?



- C Ignition at M_{Ch} Limit
(possibly many ignition points)
- Turbulent Flame Propagation
- WD Expansion -> Flame Extinction
- Issues: Rapid Time Scales!

- » Nuclear Burning $\text{C} + \text{O} \rightarrow {}^{56}\text{Ni} \dots$
- » Expansion, Unburnt C, O
- » Mixing, non-Sphericities

SN Ia Ignition

- ★ Central Region of WD is Turbulent and at the Edge of Igniting from Compression
- ★ Many Ignition Sparks Appear to Form Around the Critical Moments, Failing to Initiate the Runaway

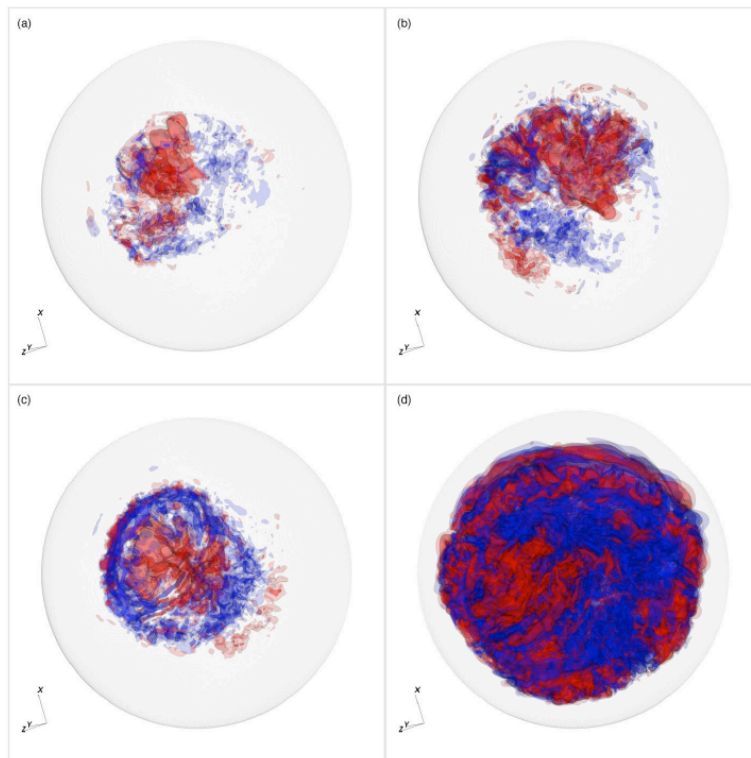


Figure 6. Radial velocity shown at 4 different times: (a) 800 s; (b) 3200 s; (c) 3420 s; (d) 7131.79 s. The latter time corresponds to the point of ignition. Red contours indicate outward moving fluid while blue contours indicate inward moving fluid. Two contour levels are used for each sign, $\pm 1.2 \times 10^6 \text{ cm s}^{-1}$ and $\pm 2 \times 10^6 \text{ cm s}^{-1}$. The gray contour is a surface of constant density, $\rho = \rho_{\text{cutoff}}$, marking the surface of the star.

👉 Zingale et al., ApJ 2009

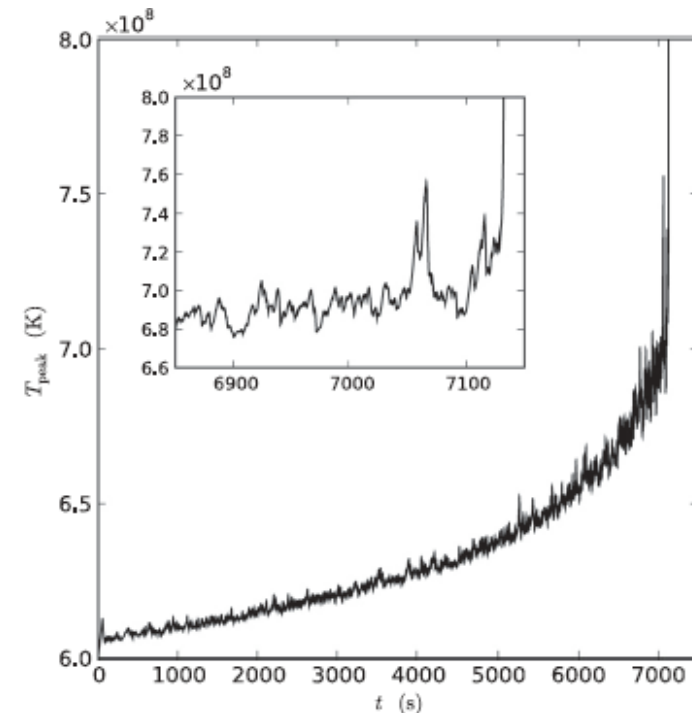


Figure 9. Maximum temperature in the white dwarf as a function of time for the 384³ calculation. The temperature increase is highly nonlinear, ending at ignition. To show detail, we restrict the vertical range of the plot to $8 \times 10^8 \text{ K}$. The inset shows the structure of T_{peak} during the last $\sim 200 \text{ s}$. We see large, but damped excursions in central temperature just prior to ignition.

SN Ia: How the Runaway Explosion Evolves



• SD's: Deflagration or Detonation?

★ Detonation (supersonic flame):

👉 Unlikely (only Fe-Group Elements);
Use as "extreme reference case"

★ Deflagration:

$v_{\text{flame}} \sim$ the size & time scale
of turbulence

(Rayleigh-Taylor, Kelvin-Helmholtz, Landau Darrius)

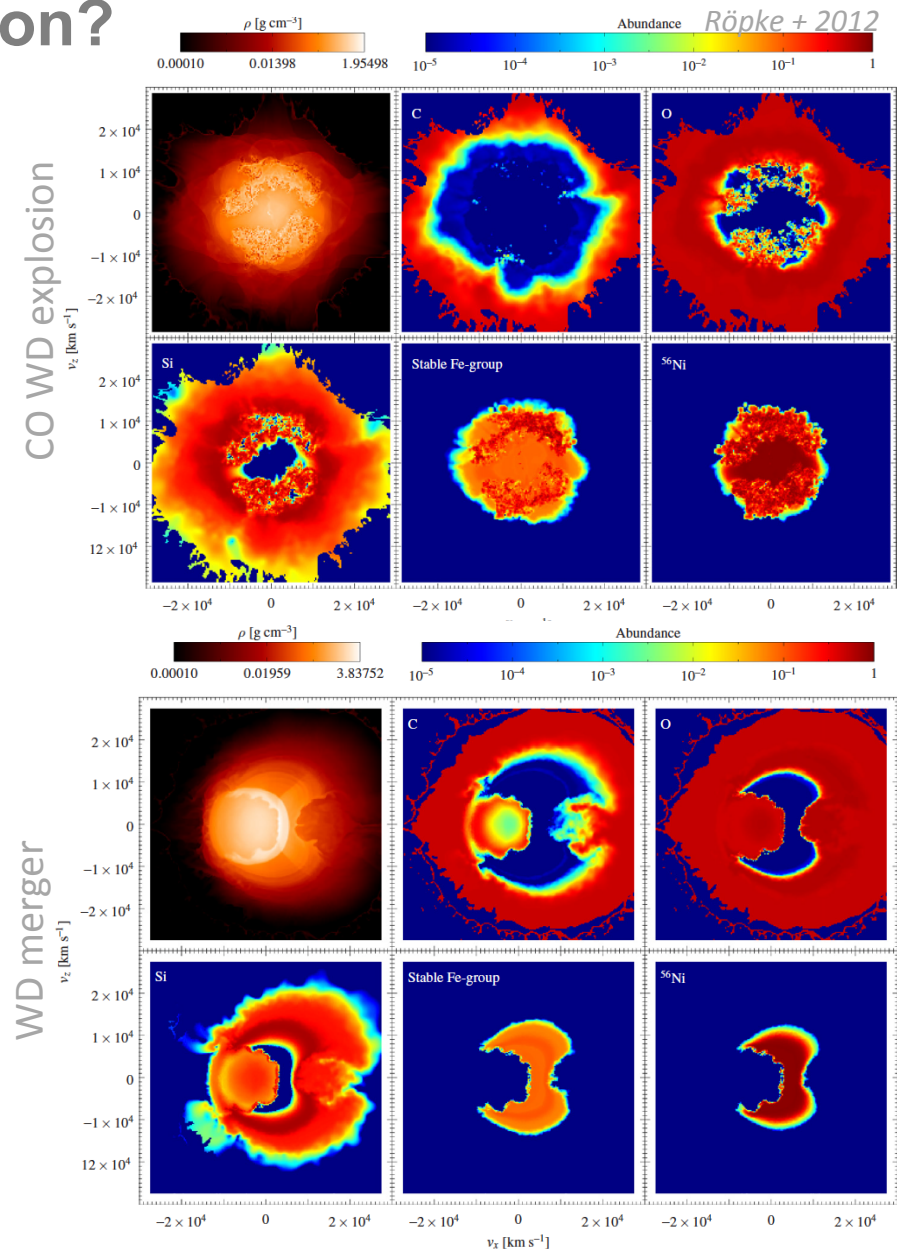
★ Laminar:

👉 Unlikely: WD Expansion
→ Fizzles

👉 Possibly 'preparing the SN'
(pulsational models)

or:

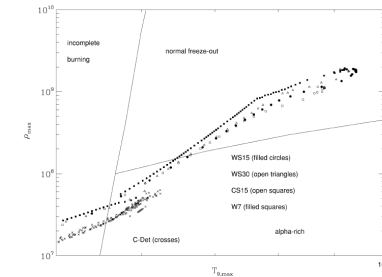
• Role of WD Mergers?



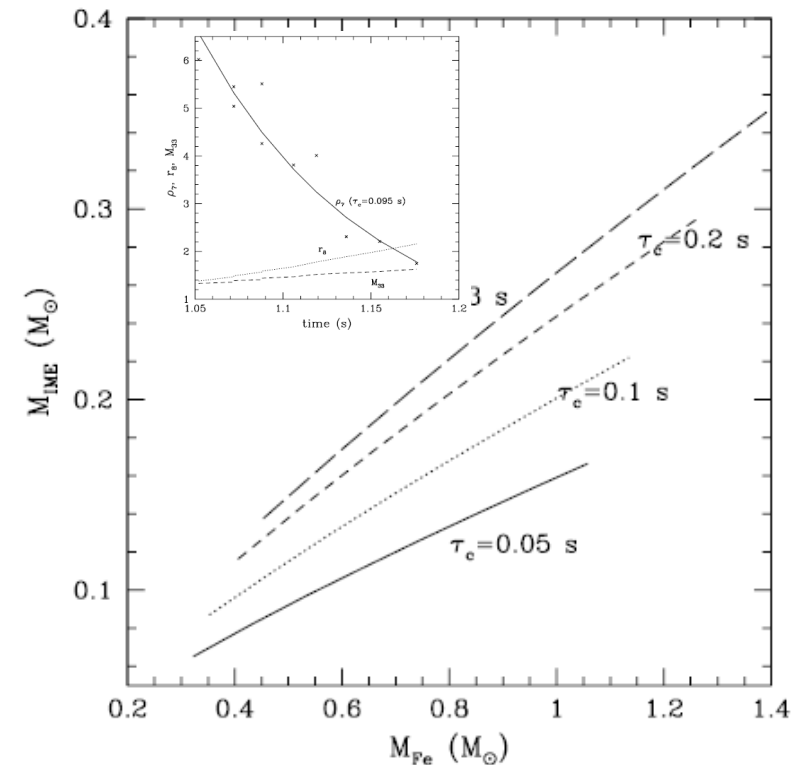
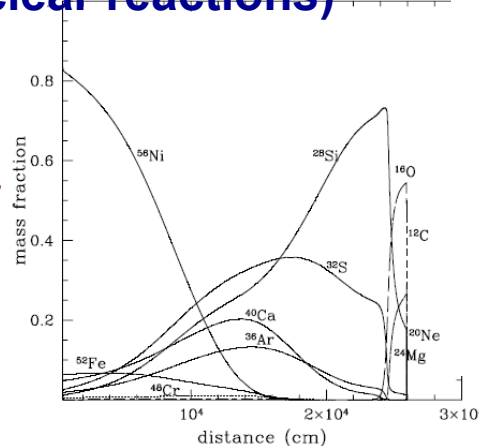
Nucleosynthesis: Fe plus Intermediate-Mass Elements



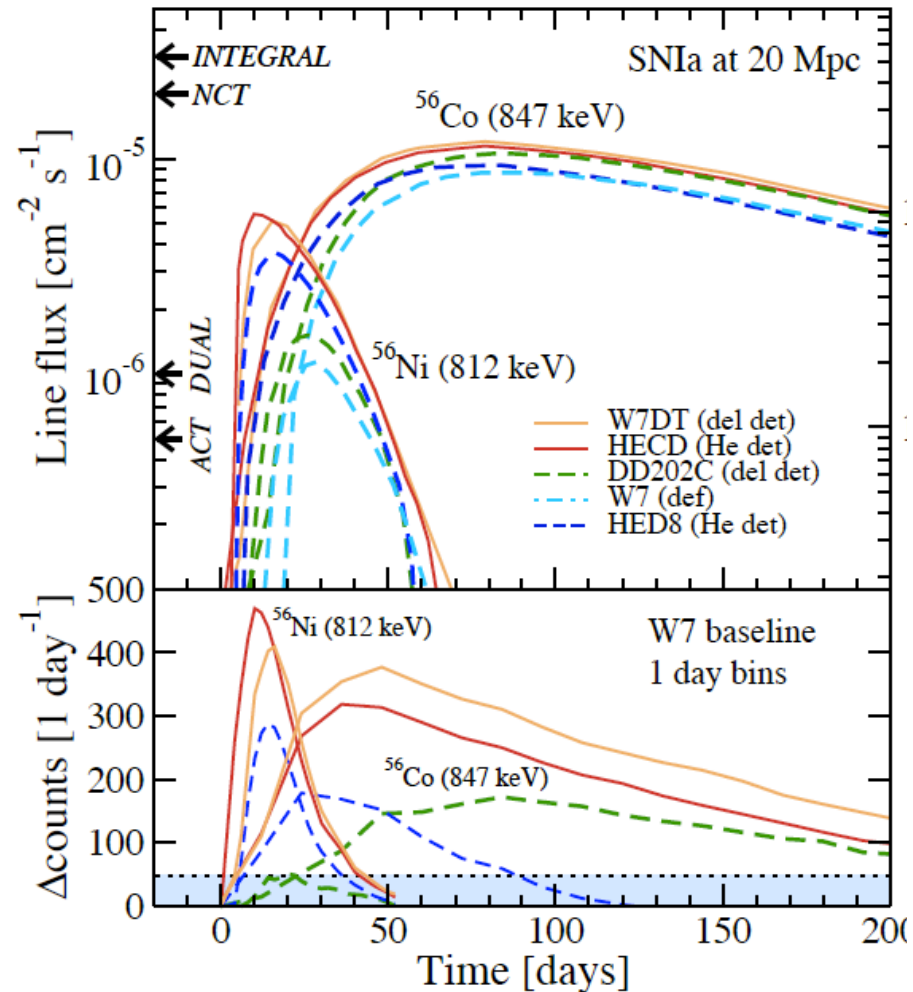
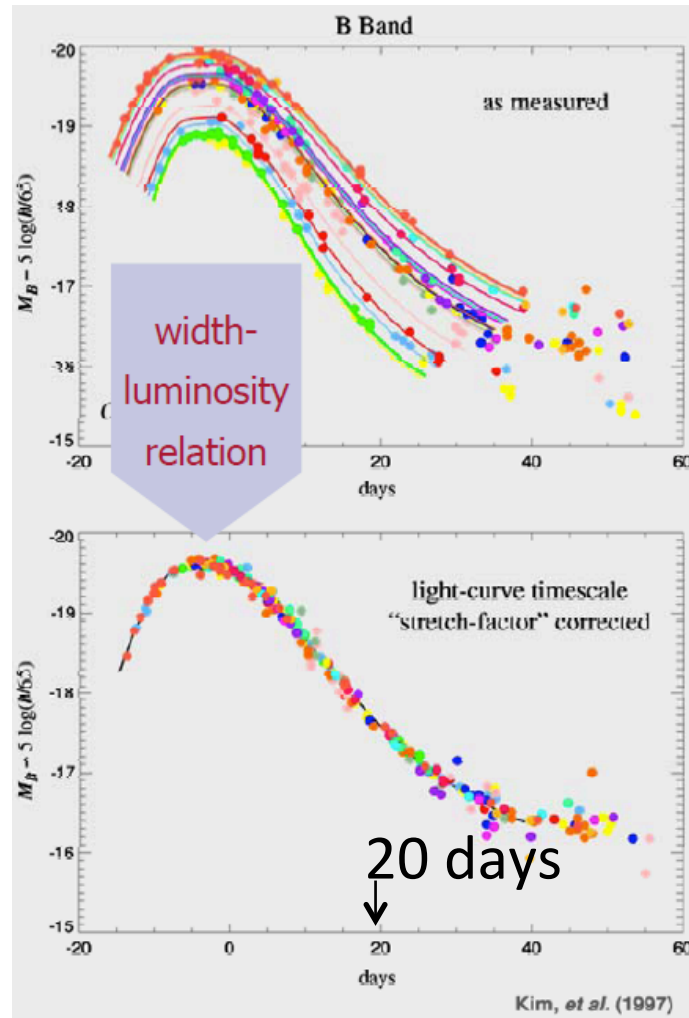
- NSE Burning \rightarrow ^{56}Ni (^4He)
- WD Expansion Time Scale / Burning Time Scale
 - ★ WD Expansion Prior to Ignition (e.g. Pulsational Model)
 - ★ Flame Speed (Determined by Turbulence \rightarrow ...Laminar)
- Freeze-Out from NSE
 - ★ Density Evolution from $\sim 10^{10} \text{ g cm}^{-3}$ (NSE) to $\sim 10^7 \text{ g cm}^{-3}$ (Incomplete Si-Burning, IME Production) to $< 10^5 \text{ g cm}^{-3}$ (no nuclear reactions)



👉 *Garcia-Senz et al. 2007*



SN Ia: Optical Light and Radioactivity Gamma-Rays



- Gamma-Calibrate SN Ia Models in Early (10d) and Late (~100d) SNR Evolution

^{56}Ni Decay γ -rays: a Nearby SN Type Ia

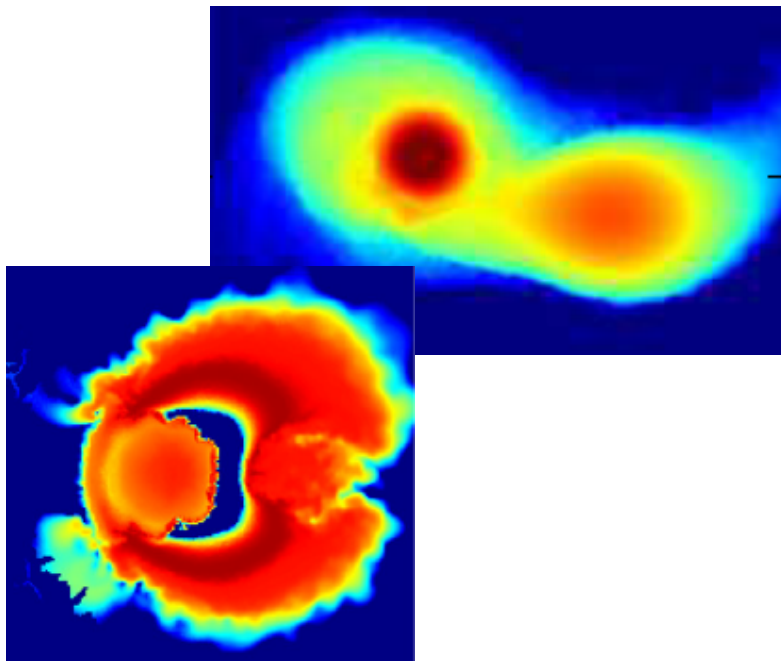
- SN2011fe in M101 (d ~ 6.4 Mpc)



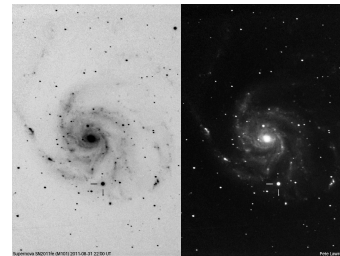
- ^{56}Ni Distribution in SN only from γ -rays



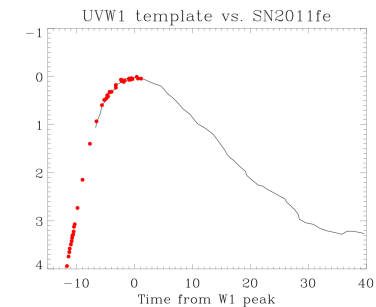
Discriminate
Among Models



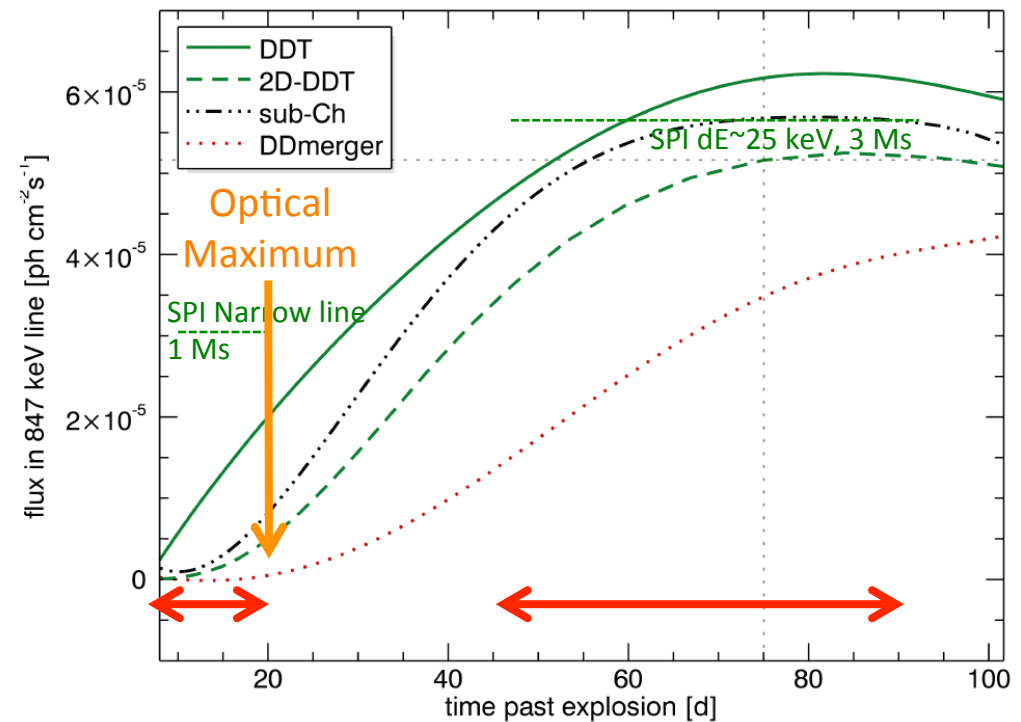
Only Upper Limit
for ^{56}Ni Decay γ -rays $\sim 1.5^{-4} \text{ ph s}^{-1} \text{ cm}^{-2}$



23 Aug 2011

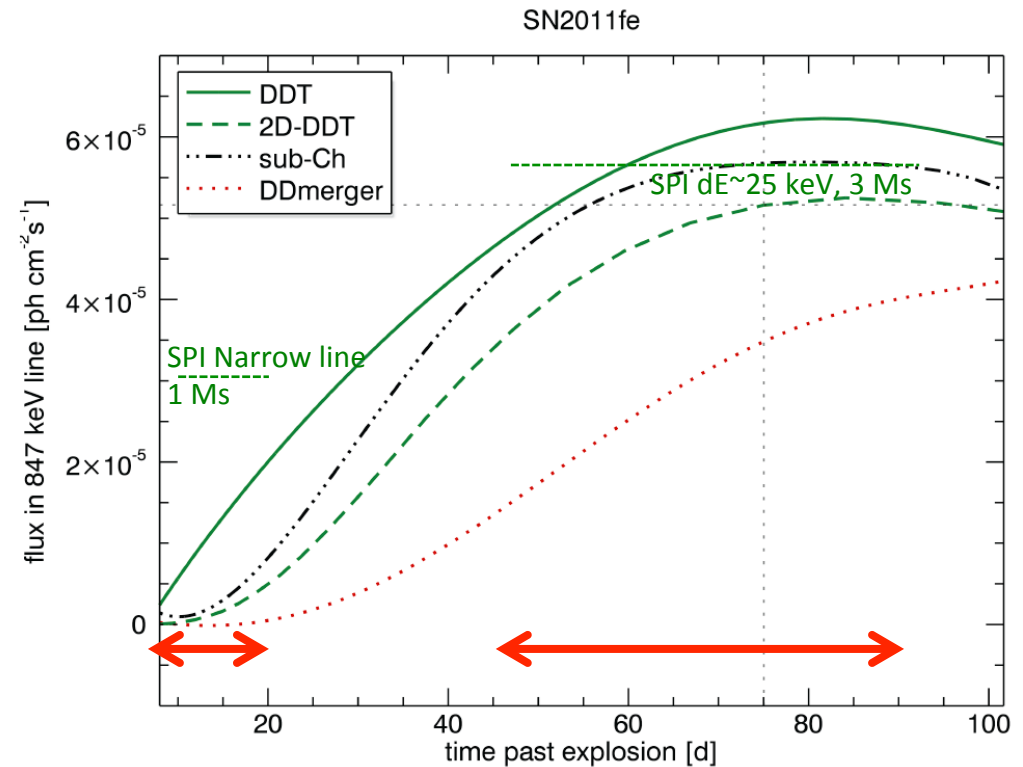
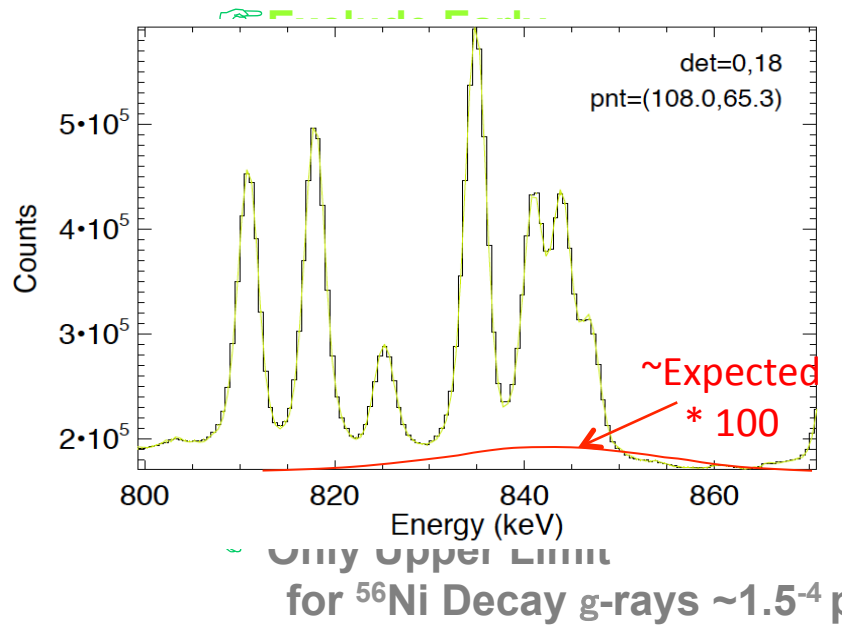


SN2011fe



SN2011fe: a Promising Opportunity

- INTEGRAL Observations for 60 d (1+3 Ms)



★ Neutron Stars as Compact Binary Component

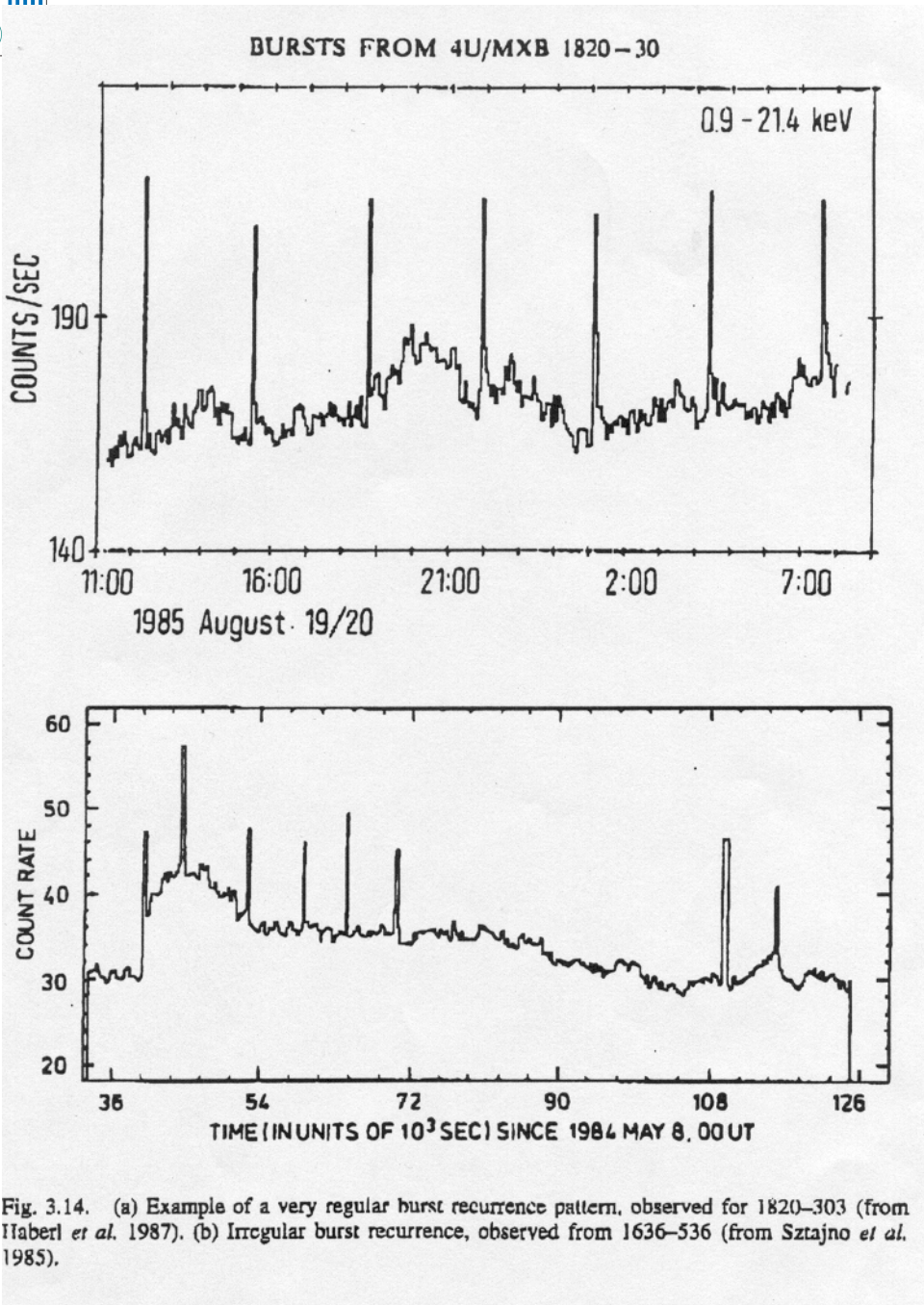


Fig. 3.14. (a) Example of a very regular burst recurrence pattern, observed for 1820-303 (from Iliabari *et al.* 1987). (b) Irregular burst recurrence, observed from 1636-536 (from Sztajno *et al.* 1985).

X-ray Bursts



Discovered 1975/1976
(Grindlay *et al.*; Belian *et al.*)

- 10^{36} - 10^{38} erg/s
- duration 10 s - 100s
- recurrence: hours-days
- regular or irregular

Frequent and very bright phenomenon !

(stars 10^{33} - 10^{35} erg/s)

Nuclear Energy in X-Ray Bursters

Energy generation: thermonuclear energy



Energy generation: gravitational energy

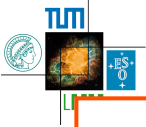
$$E = \frac{G M m_u}{R} = 200 \text{ MeV/u}$$

Ratio gravitation/thermonuclear energy ~ 30 - 40

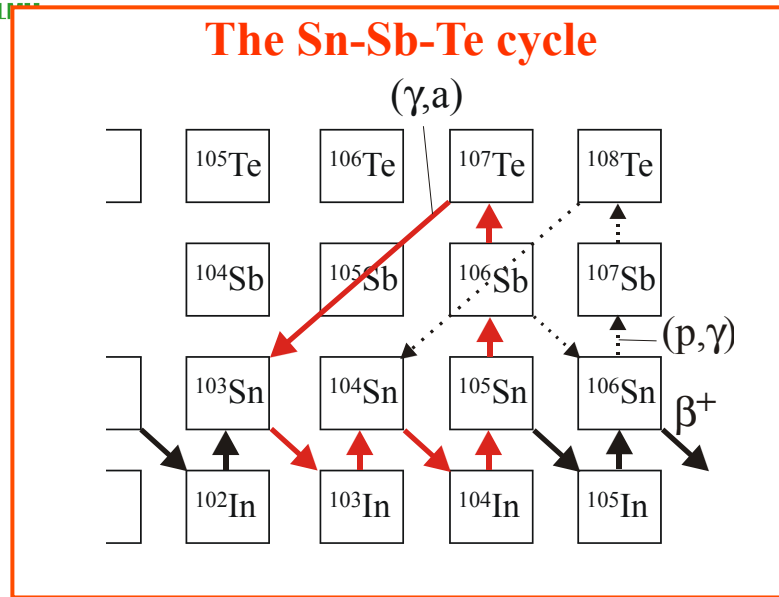
Nuclear-Burning Phases:

Ignition: 3 α

Main energy production: rp (capture of ~ 2 neutrons + β -decays)

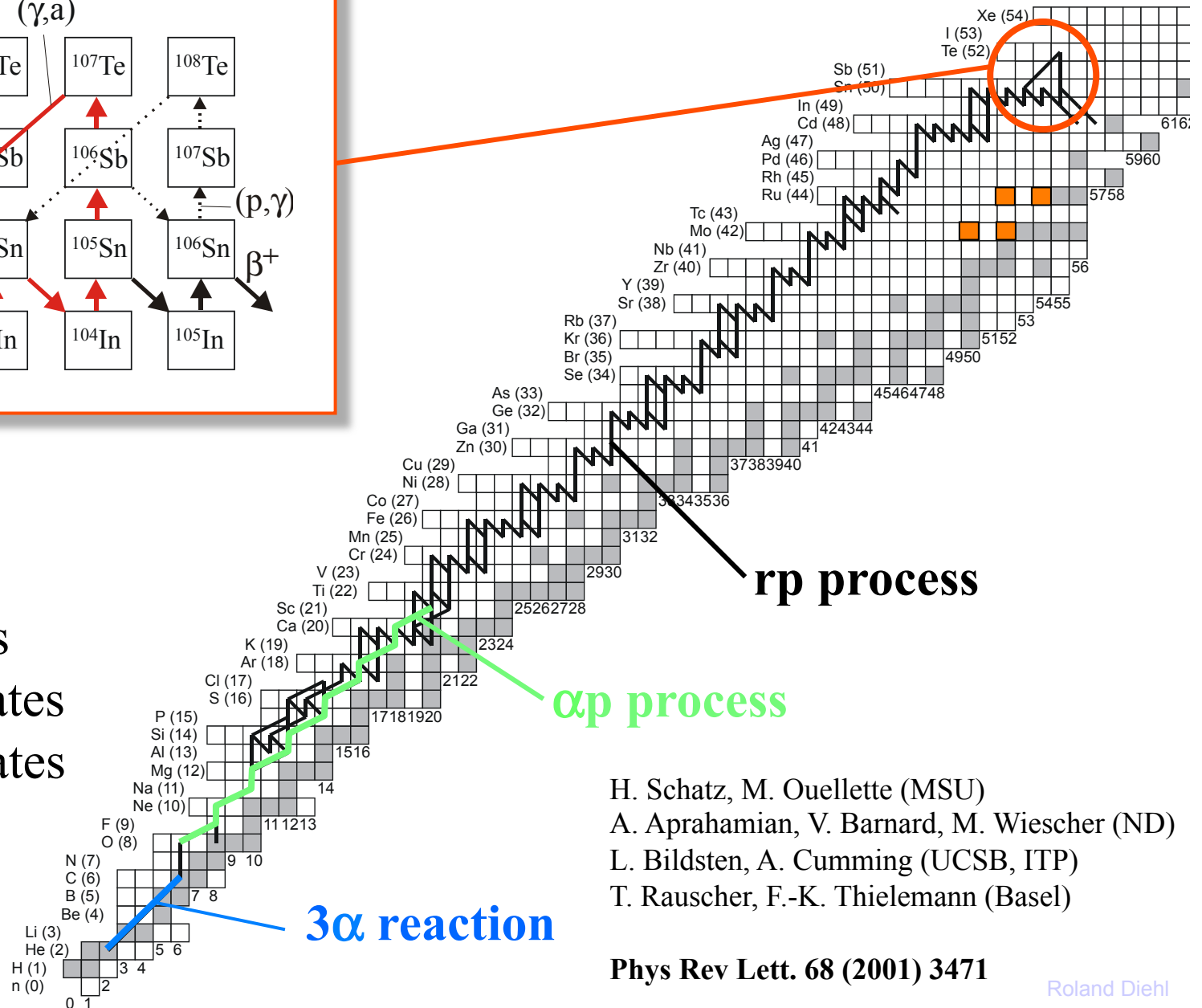


Thermonuclear burning during X-ray burst: the complete β



Data needs:

- masses (S_p)
- b-decay rates
- some (p,g) rates
- some (a,p) rates



H. Schatz, M. Ouellette (MSU)
 A. Aprahamian, V. Barnard, M. Wiescher (ND)
 L. Bildsten, A. Cumming (UCSB, ITP)
 T. Rauscher, F.-K. Thielemann (Basel)

Phys Rev Lett. 68 (2001) 3471

Nuclear Reaction Regimes on/in Neutron Stars

